



# Mitigating Health and Environmental Risks From E-Waste Dismantling via Plasma Arc Gasification WtE and Sustainable Materials Management Modeling

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Mitigating Health and Environmental Risks from E-waste Dismantling Via  
Plasma Arc Gasification WtE and Sustainable Materials Management Modeling

Angelina H. Jao

A Thesis in the Field of Sustainability and Environmental Management  
For the Degree of Master of Liberal Arts in Extension Studies

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## Abstract

Informal E-waste recycling is an epidemiological and environmental crisis of unprecedented scale and complexity in human history. The demand and scarcity of rare earths and heavy metals, compounded by the sheer volume of untrackable flows of E-waste, present both opportunity and crises. Grey (undocumented) markets continue growing in tandem with expanding shipments of E-waste. The poorest marginalized communities employ dangerously elementary E-waste dismantling methods to extract small quantities of valuable metals for subsistence-level resale. Research indicates there are many persistent and new toxicological risks to ecosystems and human health, with pregnant women and children suffering the highest chronic damage from multi-channel exposures to chemical compounds. The largest informal E-waste dismantling centers are located in the same country that manufactures the most electronics products for the rest of the world: China.

This study hypothesized decreasing elementary manual E-waste dismantling in China would directly contribute to improving human health outcomes for the most at-risk populations in China, as well as decreasing overall greenhouse gas (GHG) emissions impacting the globe. In order to move towards this goal, this study examined Taiwan's Smart Materials Management (SMM) system as a promising solution to localize to China's biggest E-waste dismantling region, Guiyu. China's reliance upon coal for electricity exacerbates GHG emissions. It was hypothesized that decreasing mechanical shredding to access printed circuit boards (the first major step of E-waste dismantling)

would directly contribute to lessening GHGs and improving health outcomes. If E-waste flows are controlled, then using plasma arc gasification to process the waste into energy can become more attractive to traditional financing, facilitating human and ecological health improvement.

In order to evaluate the feasibility of this hypothesis, the goals of this study focused upon: surveying research studies examining epidemiological toxicity of E-waste; determining a life cycle analysis (LCIA) baseline for the first step in elementary E-waste dismantling (mechanical shredding) in China compared to the rest of the world; examining Taiwan's SMM system in order to control the flow of printed circuit boards (PCBs) away from illegal enterprises to licensed processors; and selecting the best plasma arc gasification (PAG) system.

This study employed peer-reviewed literature surveys of Taiwan's SMM, global research of epidemiological impacts from E-waste processing, and LCIA studies of E-waste processing, as well as evaluating publicly-available literature of plasma arc gasification systems. SimaPro 8.0.5.13 and the Ecoinvent 3 database were used to conduct the LCIA on 1 kg of heterogeneous E-waste, using ReCiPe Endpoint (H) V1.12 / Europe ReCiPe H/A method. The focus upon the first stage of major dismantling emissions – mechanical shredding, comparing China to the rest of the world – found a LCIA single score of 3. Although this analysis was based upon Swiss data over 10 years old, and technical details about the shredders were unavailable, it establishes one baseline for comparison. This study focused upon the dismantling stage of E-waste PCBs because of both prevalence and value: every electronics product contains one, and every PCB contains valuable metals. The waste-to-energy technology focused upon was

plasma arc gasification torches manufactured by industry leader AlterNRG due to its technological advantages.

Based upon initial study results, it is estimated that mechanical shredding of E-waste PCBs in China is 30% less sustainable than elsewhere globally, primarily due to reliance upon the lignite-generated (the “dirtiest” type of coal) electricity to process the large volumes of waste. Significant reduction in health and environmental impacts are achievable if Taiwan’s SMM systems can be localized to China’s market conditions, coupled with PAG E-waste-to-energy processing systems. Although independently verified data on PAG systems are currently unavailable publicly, this study established a baseline focused on reducing emissions at the first dismantling step in China, mechanical shredding. Removing this step is central to reducing epidemiological risks. Older generation E-waste open air dumps are more efficiently reduced using PAG conversion to usable energy. This study concludes this solution is preferable to current elementary dismantling metal recovery efforts in China.

## Biography

The author is a graduate of the University of Wisconsin and the University of Maryland, with a B.A. in International Relations and English, and a M.S. in International eCommerce Marketing Management, with additional high-tech coursework at New York University and Columbia University. She was an instructor of graduate-level e-commerce courses at City University of New York, and self-defense at shelters. Earlier in life she enjoyed internships at USDA's Nematode Lab, science fair projects involving the space shuttle, soldering motherboards, musical instruments, papercutting, calligraphy (brush, old English blackletter), and martial arts.

She is a native of greater Washington DC, and her career has been based in New York City, with extensive travel throughout the Caribbean, Europe, and Asia. Most of her work has been in the fields of high-tech and industrial economic development. She is non-native fluent in Mandarin. Tinkering and creating are among her many disparate interests.

## Acknowledgements

For all those around the world who toil over E-waste, trading their lives and their children's futures doing dangerous work that we electronics consumers all need yet little appreciate, you have my gratitude. I hope to be part of the solution to the challenges of E-waste management.

I am grateful to Professor Ramon Sanchez Pina for all his assistance and unwavering support of my ideas and research throughout the challenging years I've been enrolled in the Master's program. He provided the inspiration for the PAG unit as part of my initial B2G land remediation turnkey solution, and encouraged me to pursue innovative solutions useful to policy development.

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## Definition of Terms

Biomass is biological material derived from living, or recently living organisms, including municipal solid waste. As an energy source, it can be used directly via combustion to produce heat, or indirectly after converting it to biofuel. Conversion of biomass to biofuel can be achieved by thermal, chemical, and biochemical methods.

Closed loop systems are focused on reuse of materials from manufacturing processes from the start to the end-of-life of a product (or cradle-to-grave).

End-of-Life (EoL) refers to when a product is considered to have ceased being useful, and is destined for recycling or disposal as waste.

E-waste (or waste EEE, WEEE), are electronics products that consumers consider having reached EoL. Recyclers and dismantling workers consider these materials either salvageable for resale, or destined for disposal.

Fly ash (or flue-ash), one of the residues usually generated in coal combustion, is comprised of fine particles that rise with the flue gases. All fly ash include substantial amounts of silicon dioxide ( $\text{SiO}_2$ ) and calcium oxide ( $\text{CaO}$ ). Toxic constituents include one or more of the following elements or substances found in trace quantities (up to hundreds ppm): arsenic, beryllium, boron, cadmium, chromium, hexavalent chromium, cobalt, lead, manganese, mercury, molybdenum, selenium, strontium, thallium, and vanadium, as well as dioxins and PAH compounds.

Materials Recovery Facility (materials reclamation facility, materials recycling facility, or Multi Re-use Facility, MRF) is a specialized plant that receives, separates and

prepares recyclable materials for marketing to end-user manufacturers. MRFs are generally clean or dirty types. Clean MRFs accept recyclable commingled materials. Dirty MRFs accept mixed solid waste streams, and separate designated recyclable materials through manual and mechanical sorting.

Municipal Solid Waste (MSW) is solid trash or garbage from residential sources. Plasma Arc Gasification (PAG) processes use plasma torches powered by electric arcs in oxygen-starved, high-temperature environments, converting biomass, solid hydrocarbons (such as coal, oil sands, oil shale, industrial or medical wastes) into reusable by-products of synthetic gas, electricity, and glassy solid slag.

Pyrolysis is a thermochemical decomposition of organic material at elevated temperatures in the absence of oxygen (or any halogen). It involves the simultaneous change of chemical composition and physical phase, and is irreversible. Pyrolysis is most commonly observed in organic materials exposed to high temperatures, starting at 200–300 °C (390–570 °F).

Slag is the glass-like by-product left over after a desired metal has been separated (i.e., smelted) from its raw ore. Slag is usually a mixture of metal oxides and silicon dioxide. However, slags can contain metal sulfides and elemental metals. Slags are generally used to remove waste in metal smelting, and is a by-product of PAG.

Syngas (synthesis gas) is a gaseous mixture produced from gasification processes of any hydrocarbon feedstock, composed of hydrogen, carbon monoxide, and sometimes carbon dioxide. It is used as fuel, for creating synthetic natural gas (SNG), and for creating ammonia or methanol. Primarily, it is used to generate electricity, and is



commonly fuel for internal combustion engines. Its energy density is less than 50% of natural fossil fuel gas.

Tipping Fees (gate fees) are the charges levied upon a given quantity of waste received at a MRF or landfill. It is generally levied to offset operational costs, and may also include any landfill taxes. The fee can be charged per load, per ton, or per item depending on the source and type of the waste. Costs can be high enough in some regions to justify closing a MRF or landfill in favor of other solutions such as PAG.

WtE (Waste-to-Energy), or EfW (Energy-from-Waste), is the process of generating energy in the form of electricity and/or heat from the combustion of waste. WtE uses garbage as a renewable biomass-based feedstock, and converts the waste into energy through thermal or non-thermal processes. Most WtE processes produce electricity and/or heat directly through combustion, or produce a combustible fuel commodity, such as methane, methanol, ethanol or synthesis fuels. These thermal technologies include gasification, thermal depolymerization, pyrolysis, plasma arc gasification. Non-thermal technologies include anaerobic digestion, fermentation, mechanical biological treatment (MBT).

## Chapter I

### Introduction

China is both the global leader of both electrical and electronic equipment (EEE) manufacturing, as well as the top dumping destination for used, waste EEE (or E-waste), with at least 70% of China-manufactured EEE exported back to China as E-waste. Despite Chinese central government enforcement of regulatory and border controls enacted in recent years, including several “National Pilot Projects”, the actual quantity of illegal E-waste entering China cannot be determined because of loopholes permitting mixed material imports entering from Hong Kong and Vietnam, as well as the difficulty posed by smugglers exploiting the interior waterway systems of the Pearl River Delta Estuary and the Yangtze River Delta. The United Nations Environmental Programme (UNEP) estimated up to 50 million tons of E-waste were generated worldwide in 2005, and China received, conservatively, most of that volume (UNU, 2013) (Figure 1).



Figure 1. Known and suspected routes of E-waste dumping. (Worldloop, 2015).

The volume of E-waste entering China has led to the creation of a grey market of micro-business “backyard informal workers” who distribute, disassemble, extract and resell components of E-waste. Income from E-waste dismantling is \$1.50-\$2.00/day, or more with the most desirable E-waste: printed circuit boards (PCBs), a necessary component of every EEE product. A cell phone alone contains >40 elements from the periodic table.

PCBs hold greater interest to laborers because on average, PCBs contain higher market value elements. The remaining plastic is also recyclable, or can be used as fuel stock for waste-to-energy (WtE) thermal processes. However, unwanted plastic is usually simply burned in the open air by E-waste recyclers, creating unprecedented levels of multi-pathway toxin intake.

This exposure has reached epidemiological scale, particularly impacting vulnerable population sub-segments: pregnant women, children, and the elderly.

### Research Significance and Objectives

Researchers recently conducted systematic reviews of available literature on the informal sector of electrical and electronics equipment recycling of E-waste in China, and reported that large research gaps are growing in understanding the human health burden and global epidemiological consequences of this grey market industry (Chen, Dietrich, Huo, & Ho, 2011). It was also noted that due to the scale of the problem, longitudinal studies and “solution-oriented research” are among the most needed to address the complex impacts of China’s burgeoning E-waste “calamity.”

The main goal of this study was to select one step of the E-waste informal

recycling process, then create and examine a hypothetical solution. The selected step focused upon was a life cycle inventory assessment (LCIA) of the low-tech mechanical shredding step of E-waste dismantling. The hypothetical solution created was to use a combination of two novel approaches – conducting a detailed survey of a successful localized “smart materials management” (SMM) model to evaluate adaptable policy development, and combining that model with a selected high tech application of a plasma arc gasification system (PAG). It was hypothesized that this modeling could help decrease adverse human health consequences of exposure to toxins currently released by low-tech mechanical shredding of E-waste dismantling in ecologically sensitive regions of China, led by the largest town, Guiyu, in the Pearl River Delta Region.

Testing this hypothesis may help bridge a knowledge gap in solution-focused research of the E-waste problem in China. It may be feasible to create a profitable business channel for PCB waste by tailoring a localized SMM model to ensure the waste stream reaches legitimate E-waste processing facilities, and to require facilities to have an on-site PAG facility to convert the waste plastics and toxic by-products into saleable energy. A successful version of this proposed model can help inform policy developers and enterprise administrators, facilitating more efficient E-waste processing facility installations, and helping to decrease multi-generational epidemiological impacts upon the most vulnerable human populations.

### Background

Informal or rudimentary E-waste recycling in Guiyu and other Chinese cities are valuable, necessary market services for all stakeholders. The question for producer EEE

industries, consumer and worker human populations, and supporting ecologies is: how can efficiencies and safety be achieved?

Informal E-waste recycling is an epidemiological and environmental crisis of unprecedented scale and complexity in human history. The demand and scarcity of rare earths and heavy metals, compounded by the sheer volume of untraceable flows of E-waste, present both opportunity and crises. Grey (undocumented) markets continue growing in tandem with expanding shipments of E-waste. The poorest marginalized communities employ dangerously elementary E-waste dismantling methods to extract small quantities of valuable metals for subsistence-level resale. Research indicates there are many persistent and new toxicological risks to ecosystems and human health, with pregnant women and children suffering the highest chronic damage from multi-channel exposures to chemical compounds.

The largest informal E-waste dismantling centers are located in the same country that manufactures the most electronics products for the rest of the world: China. The elementary methods of informal E-waste dismantling include mechanical shredding, burning in open air, chemical acid “cooking” and leaching (Figure 19, Appendix). These and other commonly used methods release highly toxic carcinogens, neurotoxins, other bio-accumulative persistent organic compounds (POPs), and heavy metals in the form of fumes and fine particulate matter (PM) dust. Complex human body burdens, acute illnesses, and chronic diseases result from inhalation, dermal and eye contact, and ingestion magnified by soil-crop-food pathways. Workers experience myriad health problems with every human body system, from asthma to brain damage, cancer of all types, and disturbing rates of miscarriages. Solution-focused studies are needed to

understand human health epigenetic transgenerational disease risks, and mitigating and rehabilitating chronic bio-accumulative environmental damage to food chains. Several studies highlight the causal link between E-waste chemicals and negative health outcomes, and the urgent need for longitudinal studies to address data gaps (UNEP, 2009; Chen, Dietrich, Huo, & Ho, 2011; Grant, et al., 2013; Song, 2014).

The estimated human health exposure is of epidemiological scale. As of 2011, China's population was estimated at 1.4 billion, around 19% of the world's population, with annual growth of 0.57%. Around 50.3% uncertainty prohibits second decimal as significant figure of the national population lives in rural areas, but hundreds of thousands of migrant workers move to urban areas to find work. As a rapidly developing economy with the largest population in the world, up to an estimated one million poor Chinese annually find work in the E-waste market.

The world's top two destinations for E-waste are also two of the five National Central Cities of China: Guangzhou and Tianjin (Figure 2). These mega-metropolises are situated on the Yangtze River Delta and Pearl River Delta systems respectively. These two river systems have unique ecosystems, supporting at least 200 million people. In the largest E-waste "dump" in the world, the township of Guiyu within the megalopolis of Guangdong, over 200,000 migrants and over 80% of the 150,000 residents labor in the "informal E-waste dismantling sector", directly impacting the Pearl River Delta estuary system, a critical delta region sustaining over 120 million people. The Chinese government is currently still constructing its first E-waste dismantling factory in Guiyu, but no details are available about the methodology to be used (Cobbing, 2008; UNU, 2013).

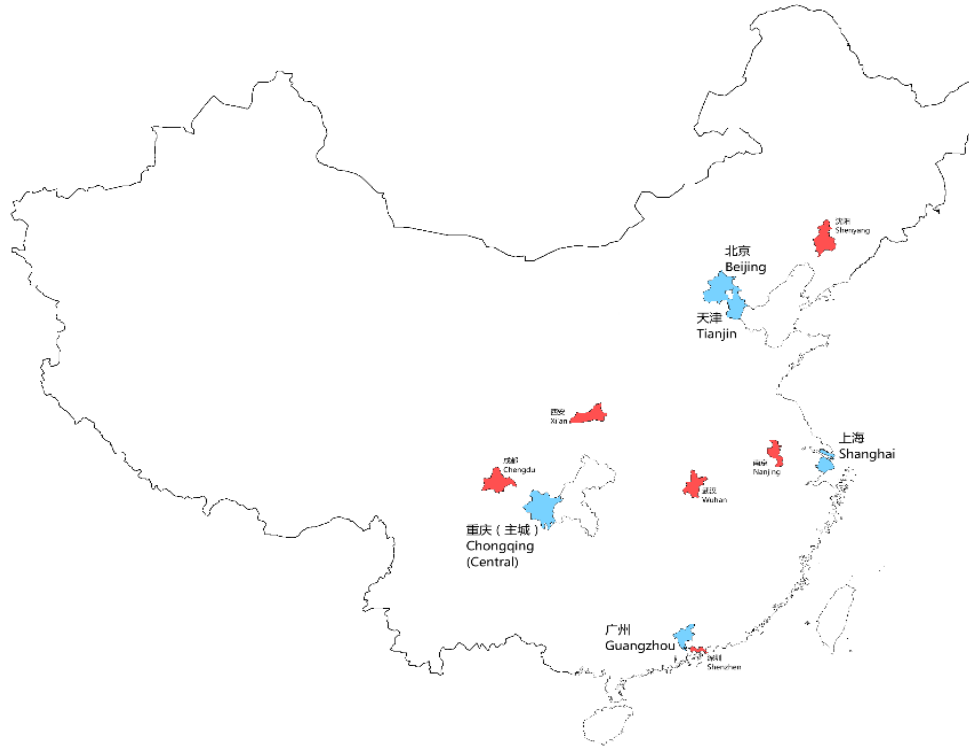


Figure 2. The five National Central Cities of China. (Wiki, 2015).

Recyclers have been reselling purportedly salvageable products to disreputable middlemen who export E-waste to dumps in developing economies, mainly China. United Nations University and U.S. EPA estimate that in 2010 alone, 14.4 million used electronics products were exported out of the U.S., weighing about 0.027 tons, comprising only monitors, computers, mobile phones, and TVs (Figure 3). TVs and monitors made up most of the weight, but mobile phones dominated in numbers of units. By a weight to desirable component ratio, mobile phones and printed circuit boards (PCBs) in general are more valuable to, and sought after by, stakeholders such as middlemen importers and E-waste workers (Duan, 2013).

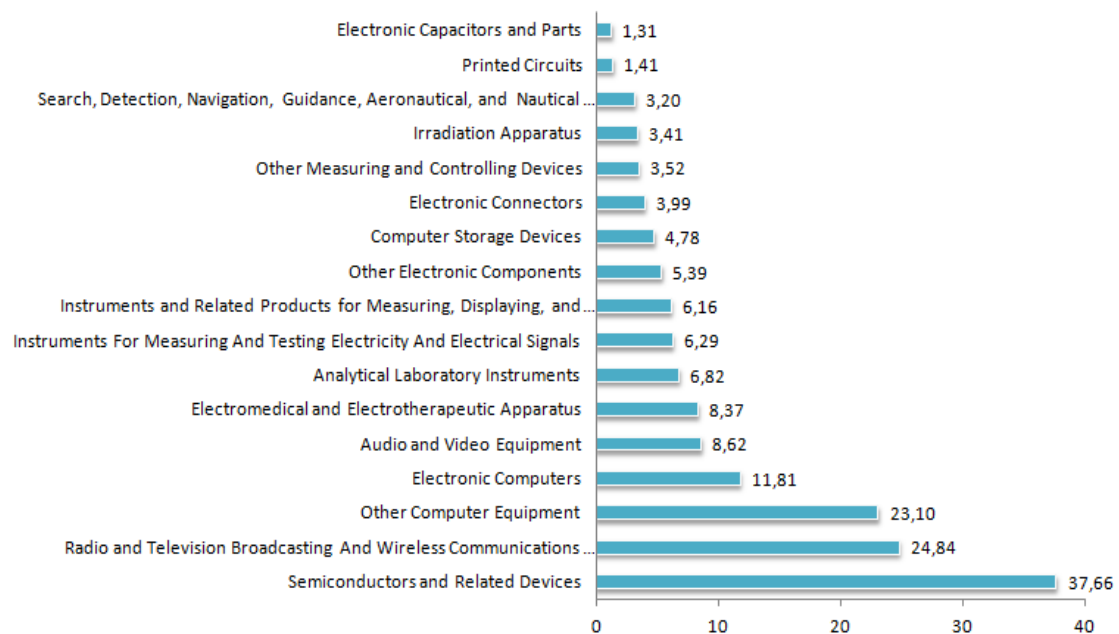


Figure 3. U.S. export of computer and electronic products. USD \$ billions, cumulative year to date through October 2011 (U.S. Census Bureau, 2011)

#### Global Production of E-waste and Volume Trends for the Future

Based upon electronic sales obsolescence projections, E-waste is the fastest growing waste stream globally, at the rate of 3-5% per annum, three times faster than municipal solid waste (MSW), and accounting for at least 8% of MSW. Conservatively, 20-50 million tons of E-waste are generated annually. Within the next 10 years, developing economies are projected to increase their use of electronics by 500%. At the same time, legacy open air E-waste dumps persist, with old but still salvageable technology, such as CRT TVs, flat panel TVs, monitors, laptops, desktop computers, and mobile phones (Xakalashe, 2012).

Half a billion computers dismantled and burned in Guiyu over the last decade have contributed to substantial multi-pathway, long-term, environmental and human health risks. This continues unabated due to the sheer volume of E-waste, and lack of



political will to enforce protections. Half a billion computers contain many toxins: approximately 6.32 billion pounds of plastic, 1.58 billion pounds of lead, 3 million pounds of cadmium, 1.9 million pounds of chromium, 632,000 pounds of mercury. Mobile phones alone have up to 45 of many of the same chemicals (Silicon Valley Toxics Coalition, 2013). Researchers estimate about 42 Mt (million metric tons) of E-waste was generated globally in 2014, and an estimated 6 Mt of this volume was ICT (information and communications technology) products related. These estimates are based upon reported sales figures to corporations or individuals, but are compounded by resale markets.

The resale market includes corporate products that may also be used as consumer products, called “dual use” products, such as laptops and cell phones. Corporations may avoid costs associated with responsible end-of-life (EoL) disposal of their products, as well as benefit from income, by using the resale market. Researchers are not able to accurately track ultimate destinations of these E-waste streams. But added together, given the widespread use of ICT in both corporate and consumer settings, the global production of E-waste is expected to accelerate, growing to 48,2 million metric tons by 2017 (106,262,810,373 pounds, or 53,131,405 short tons). There are no signs of abating, and growth is estimated at an annual rate of about 5% globally. Within this 5% rate, exponential growth is projected by as much as 500% over the next decade due to the E-waste contributions of developing economies. Researchers acknowledge the difficulty in acquiring accurate numbers due to the absent or poorly regulated nature of the informal recycling sector, as well as illegal transboundary shipments of EEE to other countries, typically developing economies – under the guise of reuse – where they can be recycled

at a lower cost, leading to increased profit for the brokers but without the safe management of the hazardous components (McCann, 2015).

Based upon electronic sales obsolescence projections, researchers know E-waste will only accelerate in volume and complexity as technology appears in almost every facet of modern life. E-waste is growing three times faster than municipal solid waste (MSW), at the rate of 3-5% per annum. Annually, 20-50 million tons of E-waste are generated. Within the next 10 years, developing economies are projected to increase their use of electronics by 500%. Legacy dumps of old but still salvageable technology, such as CRT TVs and monitors, persist but cannot be accounted for. Flat panel TVs, monitors, laptops and desktop computers, and mobile phones will continue to add to existing volumes of E-waste (UNEP, 2009) (Figure 4).

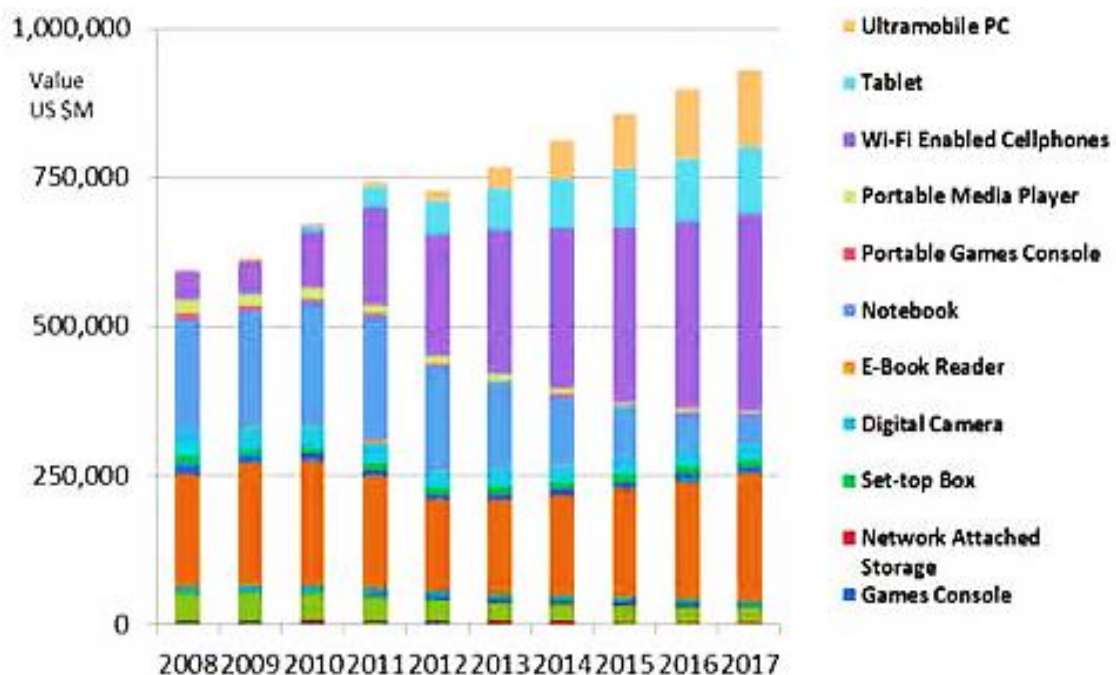


Figure 4. Global Consumer Electronics Industry Revenue 2008-2017 (Cellular News, 2013)

Corporate product producers have not been able to decrease toxic components acceptably for critics. Compounding the problem, recyclers have been reselling purportedly salvageable products to disreputable middlemen who export E-waste to dumps in developing economies. United Nations University and U.S. EPA estimate that in 2010 alone, 14.4 million used electronics products were exported out of the U.S., weighing about 0.027 tons, comprising only monitors, computers, mobile phones, and TVs. TVs and monitors made up most of the weight, but mobile phones dominated in numbers of units. By a weight to desirable component ratio, mobile phones and printed circuit boards (PCBs) in general are more valuable to exporters and E-waste laborers (Duan, 2013). The average cell phone contains about 24 milligrams of gold (UNEP, 2009) and printed circuit boards can contain 180 mg/kg to 400 mg/kg (Figure 5).

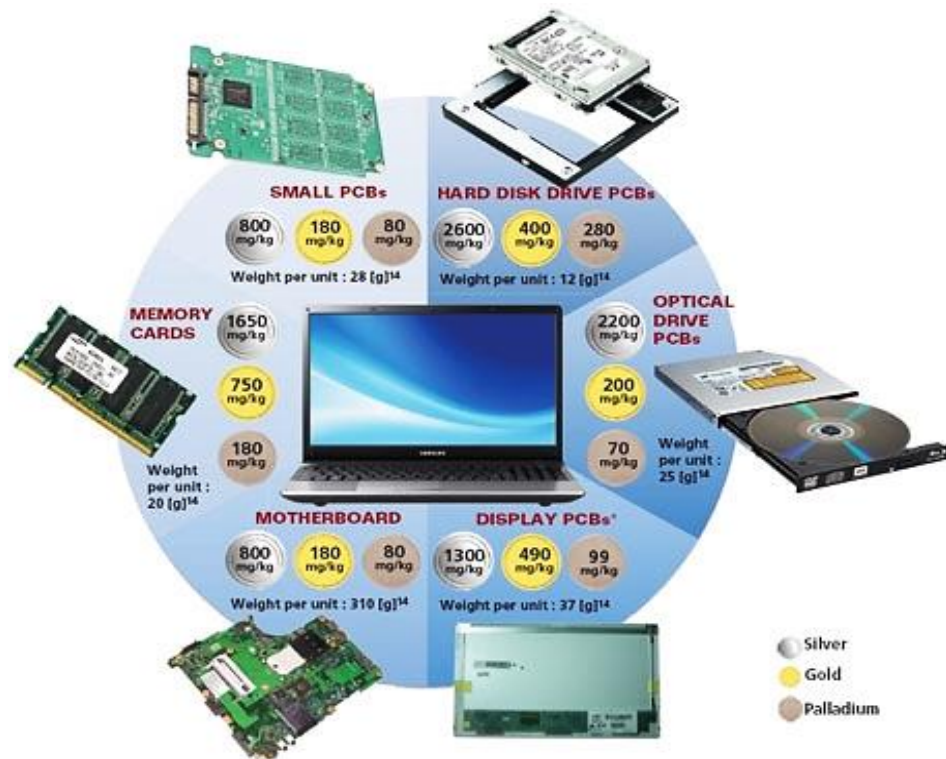


Figure 5. How much gold, silver, and palladium is in a notebook computer? (Basu, 2013)

Many stakeholders are working on new methods of extracting precious metals from PCBs, and natural resource-poor countries such as Japan, Korea, and Taiwan consider E-waste in landfills to be “urban mines.” Even within countries with enough land containing metal ores, the environmental devastation caused by mining activities makes landfill mining in comparison significantly more desirable. The value, return on investment, and risks of “landfill/urban mining” is beyond the scope focused upon in this study, but researchers and mining companies are examining these questions. Within this framework, for example, 1 ton (907.19 Kg) of personal computers can contain more gold than 17 tons (15,422.10 Kg) of gold ore, making E-waste mining (including dismantling processing, the focus of this study) highly attractive both economically and environmentally (Sumiotomo, 2015; Peters, 2011). Researchers estimated in 2009 that within the component of PCBs alone, the market value of metal recovered from 1.10 tons (1,000 Kg) of PCBs yielded 367.31 Kg of nine desired metals (Table 1).

Table 1. Market value of metal recovered from 1,000 Kg of PCBs. (Chatterjee & Kumar, 2009).

Recovered metal	Weight	Approximate value (USD)
Gold	279.93 g	\$6,115 (@ \$685.00/31.00 g)
Precious metals: Pt, Pd, In	93.31 g	\$3,852 (@ \$1,284.00/310.00 g)
Copper	190,512 g	\$1,470 (@ \$3.50/453.59 g)
Aluminum	145,152 g	\$448.00 (@ \$1.28/453.59 g)
Lead and Tin	30,844 g	\$144.16 (@ \$2.12/453.59 g)
Silver	450 g	\$213.15 (@ \$14.70/31 g)

The current elementary methods of metal recovery used in China cause far greater epidemiological risks than the small subsistence-level benefits provided workers and the surrounding ecology and communities.

Although PCBs are the most desirable E-waste components for recovering metals, researchers have not yet found the best means of recovery.

### Inherent Challenges of Recycling PCBs

Aside from costs and environmental risks, the fundamental challenge of recycling PCBs is the nature of PCB construction. PCBs take three forms – single-sided, double-sided, or multilayer. All three forms have three basic parts – a non-conducting substrate or laminate, a conductive substrate with circuits printed on or inside it, and soldered components. The substrate layers can be manufactured using different materials depending upon the use requirements (Table 9, Appendix).

The current industry standard is brominated-epoxy-based FR-4 boards – which incorporate Tetrabromobisphenol-A (TBBPA). These provide the best combination of mechanical properties, thermal stability, moisture uptake, electrical performance, and cost effectiveness, as well as low levels of failure during drilling and assembly operations, especially for multi-layer laminates. In ultra-high performance applications, “additive” brominated flame retardants perform even better than TBBPA-based boards (European Flame Retardants Association, 2015). The challenge lies in the current unavailability of brominated flame retardants present that are necessary to PCB electrical and thermomechanical performance. When PCBs are incinerated, toxic emissions are released, presenting risks to human health and the environment. In this study, the proposed technology, plasma arc gasification (PAG) operates in the absence of O<sub>2</sub>,

thereby avoiding the creation of emissions.

However, due to the ever-evolving nature of technology, and the prevalent deterioration that occurs at the end-of-life of electronics, PCB components are commonly obsolete. Usually, the desirable elements cannot even be used because the rare elements are so minute and dispersed, such as tantalum, that recovery is so excessively labor- or technology-intensive as to render recovery essentially impossible (Li, Shrivastava, Gao, & Zhang, 2004).

#### Scale of E-waste problem

China's E-waste management systems must address streams generated not only from illegal exports into the country, but also domestically generated sources. E-waste accounts for at least 8% of municipal solid waste, but is the fastest growing fraction (Xakalashe, 2012). In 2011, China's urban population was 690.80 million people, and the rural population was 656.60 million people. Researchers in United Nations University and Tsinghua University determined that in 2011, China's domestic market produced 3.62 million tons of just five types of E-waste – computers (laptop and desktop), TVs, air conditioners, washing machines, refrigerators; 0.25 billion mobile phones were sold, more than any other major electrical or electronic product sold in China. The annual growth rates and market penetration of major electrical and electronic products sold in China appliances are projected to accelerate with a conservative 45% annual growth rate for mobile phones alone (Table 2). China's domestic mobile phone market has been observed by the author to surpass the U.S. in terms of multiple units and multiple SIM cards used by each consumer at any given time.

Table 2. Units of appliances in urban and rural households. Adapted from (UNU, 2013; Duan, 2013).

Appliance	2011 Units per Urban Household	Annual Growth Rate	2011 Units per Rural Household	Annual Growth Rate	2011 Total Units (millions)
Mobile phone	2.05	27%	1.80	45%	796.60
Computer (laptop & desktop)	0.62	24%	0.18	44%	227.30
Air conditioner	1.22	15%	0.23	33%	n/a
Refrigerator	0.97	1%	0.63	18%	338.90
Washing machine	0.97	2%	0.63	8%	338.90
Color TV	1.35	1%	1.15	9%	519.70

#### Human Health Risks of E-waste Recycling in Guiyu, China

Toxic exposure impacts the most vulnerable, inclusive of migrant and local populations. Guiyu is the largest E-waste dump and processing site in the world. It is a relatively small township of four linked villages, now expanding due to a large migrant labor pool of over 200,000 people, larger than the local resident population of around 150,000. Its toxic impact upon human health, the environment, and the food chain, is potentially immense. Its rivers are part of the Pearl River Delta estuary system, an important delta region sustaining over 120 million people. Guangdong is a megalopolis – the largest urban area in the world in both size and population. It is known as the “World’s Factory”, producing over 5% of the world’s goods, accounting for over 33% of China’s trade.

Poor uneducated peasants migrate to the region for work in factories. Those who cannot find work stay in Guiyu to work in small, family-owned workshops, which specialize in dismantling types of E-waste. Lack of knowledge, absence of necessary

tools and safety mechanisms, and simple poverty have resulted in growing migrant laborers in the informal E-waste dismantling sector in many developing economies, not only China. Researchers estimate over 200,000 migrant laborers and 80% of Guiyu's 150,000 population work in Guiyu's labor-intensive, highly toxic E-waste dismantling jobs, including large percentages of children, women, and the elderly, who are all particularly susceptible to health risks caused by even relatively small quantities of E-waste components.

Diseases are also readily spread by fast-reproducing vectors – bacteria, roaches, seagulls, rats, dogs, humans – and can also enter the soil-crop-food chain pathway that includes air-borne and water-borne paths (Agency for Toxic Substances and Disease Registry, 2014).

A consortium of epidemiological researchers conducted a systematic literature review of health risks to humans and select animals within the human food chain. They found a wide range of elevated and new combinations of chemical levels associated with E-waste, indicating direct impact upon health risks (Table 10) (Grant et al., 2013).

PCBs contain higher market value elements: ~16% Cu, ~4% solder, ~3% Fe, ~2% Pb, ~2% Ni, ~0.05% Ag, ~0.03% Au, 0.01% Pd, <0.01% Sb, <0.01% Bi, and other fractional materials: precious metals, ferrous and non-ferrous metals, including gold, silver, copper, aluminum, nickel, zinc, barium, chromium, cobalt, magnet, and alloys such as solder containing lead, tin, cadmium, mercury. Very little reliable data is available about the impact upon Guiyu residents and the environment. The Chinese government, as well as local criminal organizations, have limited outside news agencies and academic researchers access to the area (Greenpeace, 2007).



Prior to the incineration step, the primitive methods used by informal workers to process E-waste such as PCBs exposes them and their environment to unprecedented levels of persistent organic pollutants (POPs), dioxins, polycyclic aromatic hydrocarbons, and toxic heavy metal elements. A Greenpeace study in 2005 collected over 70 representative samples from “backyard” workshops in Guiyu, Guangdong Province, and New Delhi, India, including indoor dust, soil, river sediment, and groundwater from the major stages of dismantling: open air dump as storage, component and plastic separation by manual destruction or mechanical shredding, chemical processing/leaching using nitric and hydrochloric acid, open burning, and waste residue dumping/burying. In addition to the emissions of heavy metals mentioned, a wide range of POPs were also found, including brominated flame retardants necessary to reduce flammability of EEE, dioxins and furans created by incomplete burning of plastics (Figure 19, Appendix).

Researchers in 2007 from Ping'an Peng of the Guangzhou Institute of Geochemistry sampled Guiyu's air and found that it has the world's highest documented levels of carcinogenic agents polychlorodibenzofurans and polychlorodibenzo-p-dioxins. Epidemiological studies are still needed to determine cardiovascular, respiratory, pulmonary, digestive, neurological, skeletal, dermatological, and other human body system diseases and cancers, brains and other developmental disabilities in children, and reproductive disabilities in women that have already been observed and documented. Guiyu's local rivers are poisoned by E-waste metallic fractions (MF), heavy metals with resale value, and non-metallic fractions (NMFs) such as carcinogenic brominated flame retardants in plastics that have no value. These plastics are often simply burned in the open air, and fumes carry particulate matter far. This is significant because Guiyu is

located within the Pearl River Delta estuary system, which sustains over 120 million people and ecosystems containing unique animals such as white dolphins, which are nearing extinction (Inocencio, 2013).

As of December 2007, researchers at Hong Kong Baptist University and University of Hong Kong were unable to find any primary studies in existence other than their own, which conducted a human health risk assessment of local dust exposure at a typical E-waste recycling site in Guiyu. They found elevated levels of lead in children (Leung, Duzgoren-Aydin, Cheung, & Wong, 2008). Households, playgrounds, children's nurseries, schools, food markets, open parks, roads, tunnels, were all found to be contaminated with heavy metal dust at elevated levels over double the maximum permitted under EU law. Inhalation, ingestion, and dermal absorption impact children more than adults given their smaller size and continuous development stages.

The rates of adult ingestion alone are estimated at 100 mg of dust/day, higher for direct scavengers themselves. "Exposure to high levels of heavy metals can result in acute and chronic toxicity, such as damage to central and peripheral nervous systems, blood composition, lungs, kidneys, liver, and even death. Lead levels in dust have been significantly associated with Pb levels in children's blood, and a blood lead level (BLL) greater than an intervention level of 10 µg Pb/dL has been associated with a decrease in IQ" (Leung AO, 2008).

The health effects upon the people of this region, and neighboring regions who use the same waterways and air currents, are at highest levels of toxic harm to children of scavengers, whom inadvertently get extra doses of toxins from their parents' clothes, skin, and hair when they return home, depositing dust on home surfaces. Studies show

neighboring villages up to 30 km away still suffer similar health effects, but at slightly lower concentrations (Leung AO, 2008).

Perhaps even more worrisome are studies showing that dust from E-waste chemicals changes scavengers' DNA. The chemicals cause oxidative stress and inflammation, precursors to DNA damage and cancer (Wen, 2008). Researchers at University of Cincinnati (UC) note, "Exposure to this type of metal mixture and persistent organic pollutants is truly unprecedented," It's the complex mixture of metals—lead, mercury, cadmium, chromium and polybrominated diphenyl ethers (PBDEs)—that concerns scientists. Many of these substances alone cause adverse health effects in humans. UC researchers believe pregnant women—and more specifically their growing fetuses and young children—living in developing countries where primitive and informal E-waste recycling occurs are at increased risk for neurotoxicity. "We need a better understanding of the human health effects of mixture exposure in order to develop effective measures to protect the people who are most at risk," note UC researchers, who in 2010 received a highly competitive \$1.7 million National Institutes of Health grant to conduct a population-based study aimed at determining how exposure to this complex E-waste toxicant mixture impacts human health. It will be the first major international population study to examine the human developmental effects of complex metal and organic pollutant mixtures found in E-waste (Harper, 2010).

In 2008, Greenpeace reported on samples their researchers had taken onsite in Guiyu, and found Guiyu children suffer asthma, lead poisoning, and often multiples of the eleven human body systems damaged at the organ level, inhibiting organ function, or at the cellular level, causing cancer (Cobbing, 2008).

## Case Study: The Potential of Taiwan's Sustainable Materials Management (SMM) Model

### Ministry of Environment and Natural Resources (MENA)

An island nation of only 13,973 sq. mi., nearly all of Taiwan's 23.3 million people live on the coast of the western one-third of the island (U.S. Dept. of State, 2012). The other two-thirds of the island is mountainous (Directorate General of Budget, Accounting and Statistics, Executive Yuan, R.O.C., 2012). Climate change and rising sea levels are a pressing concern, but Taiwan is also worried about economic survival, which is closely tied to energy security due to its dependence upon electronics manufacturing, an export-driven economy, and deriving advantages from improving systems without additional costs (Jao, 2012). This is TEPA policy-makers' framework as they work with the private sector to rethink how products can be manufactured using less energy, and how materials can be recovered, including accepting back products at end-of-life (TEPA, 2012).

Although not an official member of the UNFCCC, OECD, Basel Convention, or other international environmental conventions, Taiwan is committed to the same greenhouse gas reduction standards and is fully dedicated to achieving a "zero-waste" society as rapidly and efficiently as possible (Shen, 2012; TEPA, 2011). TEPA adopted the "Extended Producer Responsibility" concept from German policies, where manufacturers have a responsibility for the materials in its products from cradle-to-grave, and infused it within TEPA's Waste Management Law.

A total of 118 agencies were merged into the new Ministry of Environment and Natural Resources (MENR), and select laws are being merged to improve efficiencies, including the Waste Management Law and the Resource and Recycling Law. SMM

policies and regulations are continuously re-evaluated for results. The Legislative Yuan of Taiwan, the body that passes and promulgates laws, is informed or advised by Ministries within the Executive Yuan (which is the highest or central level of government) (TEPA, 2012). SMM-related policies are administered by the Executive Yuan-level TEPA and Ministry of Economic Affairs (MOEA). Within the MOEA, the Bureau of Energy (BOE) and the Industrial Development Bureau (IDB) work with TEPA and municipal EPAs to improve policies and regulations for industries, particularly key industries identified by the Ministries as critical to Taiwan's economic strength.

Taiwan's Environmental Protection Administration, Executive Yuan, of the Republic of China (Taiwan), created a new ministry that began operating January 1, 2012, to meet the rapidly evolving needs of the nation: the "Ministry of Environment and Natural Resources" (MENR) (TEPA, 2011). MENA has robust resources: seven departments, ten third-level agencies, and a staff of over 14,000, more high-tech resources, and an increased focus on expanding the legal instruments and mechanisms that have enabled Taiwan to achieve record sustainability results in waste and sustainable materials management (SMM). As source reduction programs and educational programs continue to involve more enterprises and citizens, and laws are combined for greater efficiency, TEPA's policy goal remains the same for MENR: achieving "zero-waste" throughout Taiwan, by applying the mechanisms of the "4-in-1 Recycling System" and the technology of the Industrial Waste Control Reporting System (IWCRS).

Taiwan's present and near future SMM goals include two investment-heavy, high national security priorities central to the economy: sourcing energy and rare earth metals, both critical to Taiwan's export-driven and electronic products-heavy industries. Taiwan

annually imports over 98% of its raw materials and energy, accounting for about 15% of GDP, severely impeding economic development, as well as threatening energy security. Almost half of the electricity generated is from imported coal, and coal-fired thermal power plants are Taiwan's primary greenhouse gas emitter. Moreover, due to China's obstruction, Taiwan has no international energy cooperative agreements to lessen its dependence upon coal and oil imports, as well as exposure to market fluctuations.

In comparison to neighboring peer or competitive trade economies of Japan and South Korea, Taiwan has consistently emitted much more carbon dioxide. In years 2007-2011, Japan's carbon dioxide emissions had averaged 0.258 metric tons, South Korea 0.556 metric tons, Taiwan 0.667 metric tons. This trend is anticipated to continue, and Taiwan's energy strategy is focused on security, efficiency, and protection of the environment.

The two state-owned energy companies, Taipower and CPC, have difficulty raising prices for income to upgrade energy facilities, primarily due to consumer resistance and political inertia. MENA, along with the Bureau of Energy (BOE) within the Ministry of Economic Affairs (MOEA) continues to support private energy supply companies (ESCOs) with financial aid and technology to upgrade their energy production facilities, and to encourage renewable energy development. However, despite research institutes' projects, and broad recognition of energy security vulnerability, Taiwan's National Security Bureau does not yet appear to be involved with the development of renewable energy facilities (Liao & Jhou, 2013).

In recent years, increasing global demand for rare earth metals (REM) has encouraged research and development investment into "urban mining" of existing landfills (landfill mining) for metals needed for industry, most notably electronic products

manufacturing. Recovering valuable metals such as copper from landfilled E-wastes is more effective than importing under increased global demand and tightening export restrictions of other countries stockpiling rare earths (Reuters, 2011). There are around 404 landfills in Taiwan, and TEPA plans to evaluate these for material and energy recovery, as well as adding bioenergy capabilities to thermal power plants that currently use incineration. Taiwan currently has 26 large-scale waste incinerators, and TEPA hopes bioenergy add-ons will help lessen some of the fossil fuel and rare earth imports annually (WMW, 2011).

In a July 13, 2012 report, TEPA stated, “The proper treatment rate of municipal solid waste [in the Republic of China] has reached 99.99%” (TEPA, 2012). Driving TEPA’s policy development is a sense of urgency about the island nation’s economic and environmental needs. Achieving a “zero-waste” society is central to the government’s strategy. “Sustainable materials management” (SMM) of municipal and industrial waste must be integrated into daily life, and consensus amongst all stakeholders is the key to successfully meeting the needs of the nation. TEPA and the Ministry of Economic Affairs (MOEA) proactively outreach and work with non-governmental organizations to educate municipalities, industrial waste generators and haulers, and general citizenry about the environmental and economic risks; and the necessity for new laws and regulations to more efficiently achieve a zero-waste society. Government agencies also incorporated input from stakeholders, and responded to needs by creating specific subsidies for jump-starting new waste management businesses that are critical to achieving zero-waste objectives (TEPA, 2012).

As a leading manufacturer of electrical and electronics equipment and products,

Taiwan's export-driven economy is dominated by resource-hungry manufacturing industries, including: electronics, communications technology, consumer packaged goods (CPG), integrated circuits, textiles, and plastics. Promoting local development of renewable energy sources is a top priority, and while solar and wind are popular, the island's geography is problematic. As of September, 2013, no offshore wind generation facilities have been built. Solar PV is also limited by the island's limited land (Liao & Jhou, 2013).

Sustainable materials management (SMM) in a closed-loop system is particularly critical to controlling costs in industries with thin profit margins. Taiwanese manufacturers, particularly electronics industries, are highly aware that their international competitors, particularly South Korea and Japan, are supported by government subsidies and therefore have significant competitive advantages (Jao, 2012; Shen, 2012).

#### Drivers Behind Strategic Policy Development – Gaining Consensus: Industry

Given the economic and energy security priorities that Taiwan faces, it is conceivable that under the new MENR, industries will increasingly face new regulations protecting the environment and preserving recyclable materials, but will also likely see new operational or production savings as a result of TEPA and MOEA capacity-building programs and subsidies.

On April 20, 2012, Minister Yen-Shiang Shih and the IDB produced fifteen seminars around the nation, "Industrial Energy Conservation Seminar Series", attended by over 1,500 manufacturer representatives. During these brainstorming sessions, the IDB shared cutting-edge technologies on energy and sustainable materials management to help



manufacturers improve energy operational efficiencies. Manufacturers, in turn, expressed “views and demands” about government grants, subsidies, and soft loans. Out of 280 manufacturing companies that attended, 46% are in direct competition with South Korea in critical industries such as: textiles, machinery, metal products, medical equipment, information and communications, and flat panel displays. The upcoming series will expand the program to include 378 manufacturers in key industries. (MOEA, 2012)

On June 14, 2012, the IDB organized a “cooperation platform” between Taiwan’s environmental industry and six strategic economic development agencies: American Institute in Taiwan (AIT), the British Trade & Cultural Office (BTCO), the German Trade Office Taipei (GTOT), the Australian Commerce and Industry Office (ACIO), the Canadian Trade Office in Taipei (CTOT) and the Netherlands Trade & Investment Office (NTIO). The IDB aims to promote market cooperation and investment in environmental businesses, with a particular emphasis on renewable energy (MOEA, 2012).

#### Drivers Behind Strategic Policy Development – Gaining Consensus: Communities

Taiwan’s EPA (TEPA) was only founded 25 short years ago in August, 1987 (TEPA, 2012). Since then, the country has amassed a \$466.8 billion GDP and the world’s fourth largest foreign reserves, consuming 220.8 billion kWh of electricity annually, and exporting \$325.1 billion worth of products, mainly electronics (U.S. CIA, 2012). Taiwan is one of the global leaders of high-tech manufacturing, particularly electronics, and is an indispensable element of global supply chains, with an export-based economy closely tied to the U.S. (U.S. Dept. of State, 2012). In four decades, Taiwan’s economy has grown exponentially, and waste flow, energy and raw material worries have also grown for policy-

makers, companies, and citizens. How has it managed the tremendous waste streams from economic growth?

When posed this question in early August, the head of TEPA, Minister Stephen Shen observed succinctly, “[The] political will of the [Taiwanese] people is very strong.” He added, “[Taiwan’s] NGOs are very strong, and [they] model good environmental stewardship action to the general public.” These non-governmental organizations (NGOs) include what Minister Shen referred to as “mama groups”, or activist community groups dominated by mothers.

Minister Shen observed that working with NGOs to build consensus is important to changing behavior, and if people understand the importance of coming to a consensus and adjusting their daily behavior to protect the environment and the economy, then change will occur (Shen, 2012). In recent years, the TEPA has levied fines against NGOs who have not fulfilled their commitments in educating the public about SMM (TEPA, 2012). Although this sounds simple, effecting results through policy development isn’t that simple. To achieve SMM policy goals, the TEPA developed a unique, all stakeholder-inclusive mechanism to achieve SMM policy goals: the “4-in-1 Resource Recycling System. (Table 3).

#### The Strategic Framework of Getting to “Zero-Waste” – A Unique Mechanism

The concept behind TEPA’s comprehensive program, the 4-in-1 Resource Recycling System, is to build buy-in and consensus to accelerate SMM. It includes four interconnected, systemic components comprised of embedded stakeholders, each with their own priorities. TEPA and MENA established this framework of systemic or

interdependent components to ensure achievement of the Zero-Waste policy protecting Taiwan's limited natural resources. The goal of protecting existing resources includes reduction and eventual elimination of all legacy landfills, replaced by a lesser number of high-tech landfills with recycling components eventually to be integrated into this 4-in-1 system.

At present, TEPA and MENA claim both this framework and system are unique mechanisms successfully achieving SMM resulting in a sharp reduction of known dump sites and corporate compliance, resulting in 80% of corporations in their database reported as properly disposing of industrial wastes.

Table 3. Taiwan's 4-in-1 resource recycling system. Adapted from (Shen, 2012).

System Components	Goals
Communities	Community-based NGOs are organized to promote and encourage citizens to self-separate garbage at their residences and workplaces.
Recycling Industries and Private Sector Participation	Encourage development of the private recycling industry, and purchase recyclables from Communities and Municipal Garbage Collection Teams.
Municipal Garbage Collection Teams	Separate and collect resources (MSW and recyclables), and provide a predetermined portion of proceeds from sale of resources to participating organizations and workers.
Recycling Management Fund	In order to efficiently regulate the resource recycling activities in Taiwan, the TEPA established the Recycling Fund Management Board (RFMB) in 1998. (TEPA, 2009) The RFMB is a three-committee body responsible for handling the receipt and reimbursement of clean-up, treatment and recycling fees, administration of and consulting with the recycling industry, establishing a verification scheme, and subsidizing local governments in recycling as well as promotion of resource recycling activities. TEPA sets fees which not only manufacturers, but also importers, must pay into the Recycling Management Fund, which supports 4-in-1 Recycling System program costs (including actual collection and recycling work, subsidies for education, auditing, and certifications).

Waste Disposal Act, Resource Recycling Act, Enforcement with Technology, IWCRS

The 4-in-1 mechanism works well due in no small part to the laws, regulations, and enforcement tools TEPA regularly updates to reflect changing conditions. Currently, the most common SMM method of Municipal Solid Waste (MSW) and industrial waste (IW) in Taiwan is source reduction and reuse. The Resource Recycling Act (TEPA, 2009) requires fourteen categories of materials be reused: containers made of iron, aluminum, glass, paper, plastic, containers of pesticides, batteries (general and lead acid), vehicles (autos and motorcycles), tires, lubricants, electronics and IT products, household appliances, and light bulbs.

Enforcement of Taiwan's Waste Disposal Act (TEPA, 2006) has teeth. TEPA applies what Taiwan does best: robust digital technology tools. Since 2000, specific industries have been required to use TEPA's user-friendly online waste tracking and reporting system, the Industrial Waste Control Report System (IWCRS), to report waste within 24 hours after waste has been shipped, received, or completely treated. The Act also stipulates that all garbage trucks must have permits for transportation and disposal, as well as global positioning systems (GPS) tracking systems installed, transmitting the truck's location every 30 seconds to the IWCRS. Trucks are also required to pass specifications and maintenance tests. As of 2011, 5,872 trucks had passed the test out of an estimated 7,000 in operation nationwide (TEPA Industrial Waste Control Center, 2012). Industrial hazardous and toxic waste trucks are closely monitored, and employ barcode scanners to check manifests and compare data between generators and transporter's disposal routes. If one of these trucks leaves its route, or enters a water source protection area, alarm systems will automatically dispatch inspectors, who have handheld personal

digital assistants (PDAs) connected to the system, for on-site investigations. In 2010, 432 suspected violations were discovered, and 58 citations were issued (TEPA, 2012).

The IWCRS is the most visited website of all Taiwanese government websites – approximately half a million businesses, basically all major industrial waste generators, use the reporting system (Shen, 2012).

On December 30, 2011, EPA brought online its Illegal Dumping Management System to create a database of dumps sites around the country, using GPS satellites to discover unreported sites (China Post, 2012). Database auditing and mining assist inspectors in discovering violations, which trigger on-site inspections of waste generators. The Act stipulates stiff fines and penalties for corporations and individuals who violate the law, including up to NT \$15 million (~USD \$500,000) in fines and three years to life imprisonment for the most serious cases where human injury or death is proven. The EPA mandates over 10,000 on-site inspections annually, but acknowledges that more inspectors are needed, and has implemented an education, training, and certification system to address any possible false reporting. Approximately 90,000 factories, 20,000 medical institutions, and 20,000 new demolition sites have been counted as sources of industrial waste, generating 23 million metric tons annually. There are 170 illegal dumping sites classified as severely polluted across the island (TEPA, 2012). These and other investigations resulting from new policies are currently being calculated (Houng, 2012).

#### Stakeholders, Achievements, and the Promise of Zero-Waste

As a result of enforcement policies, significant improvements continue to be documented. Between the 2004 implementation of the garbage separation policy and

2011, the amounts of materials collected have vastly changed: MSW collected dropped 38.41%, recyclables collected increased 96.56%, and kitchen garbage collected increased 171.06%. The rate of recyclable materials collected has been calculated by the EPA to be at 40.4% in 2011, or 3.05 million tons recycled. The rate of kitchen garbage recycled has been calculated at 10.74% (Houng, 2012). By September, new regulations for registering, managing and closed-circuit TV (CCTV) monitoring of resource recycling will go into effect to improve the 10,000 formal and informal recycling centers around the nation (TEPA, 2012).

In 2010, about 16.8 million tons of general industrial wastes were reported by industries (or “generators,” including factories, hospitals, and office-based enterprises), garbage truck haulers (“transporters”), and “TSDFs” (treatment, storage, and disposal facilities). The Act requires 25,861 generators, 4,963 transporters, and 865 TSDFs to make online reports on the IWCRS, although over 466,000 firms now use the system. These generators represent 22% of the total generators on the island, and generate 80% of the waste annually. The remaining 20% of waste are generated by small-quantity generators. As of 2011, 80% of industrial waste and 90% of medical wastes have been properly disposed.

The EPA’s system provides savings and efficiencies to generators, by allowing generators to self-audit, even enabling parent companies control over reported data of its subsidiaries. Reporting functions are robust, including capabilities such as statistical analysis of temporary waste storage, permitted quantities of waste, disposal quantity trends over time, GPS tracking inquiries, as well as automated alert systems.

The IWCRS also permits waste disposal facilities to track quantities as well as

condition of post-treatment materials for possible reuse. All waste is accounted for. The system audits waste manifests against permits for disposal, treatment, and recycling (Huang & Cheng, 2011). Illegal dumping is now nearly controlled, with a shrinking number of cases being pursued by TEPA. “We have removed the illegal economic advantages of the violators,” stated Minister Shen.

In 2009, the EPA signed an agreement with five major portable computer manufacturers, resulting in 3,700 tons of packaging waste reduced in 2010 alone, far exceeding the original target of 840 tons (TEPA, 2011). As a result of this success, by March, 2011, the EPA had expanded the program to include eleven more leading companies in branded household products and the packaging design industry, resulting in the Voluntary Packaging Reduction Agreement (TEPA, 2011).

By July, 2012, TEPA had amassed an extensive list of multi-national corporations that had cooperated in its programs, and recommended a short list to be contacted for quotes saying that cooperating with TEPA’s policies were beneficial to their companies. The largest industries represented were electronics/communications technology and packaged consumer goods: ASUS, AUO, BENQ, Chimei Innolux Corp., Chunghwa Picture Tubes, Ltd.; and Cha-Tei, Coca-Cola, Isabelle, Puerh Chang Tea Business Co. Ltd., Taiwan Tachi Ta Fang, Tetra Pak, Watsons, Young Energy Source Co., Ltd.

#### From Incinerators to Bioenergy Generators

The effectiveness of SMM has resulted in 80-84% of industrial wastes being recycled, and the remaining 15% treated by the waste generators themselves, or through contracted professional services. Proper treatment of hazardous wastes is now at 60%, and

TEPA and MOEA are evaluating ways to improve this rate (TEPA, 2012). In March 2012, TEPA announced a new NT \$20 million (~USD \$666,667 USD) fund to award grants for R&D into recycling methods and carbon footprint calculations for recycling methods for waste bio-plastics, waste electronic and electrical goods, and each category of spent battery; all products posing particular challenges to the existing resource recycling system. The maximum grant payable to a single proposal has been set at NT \$2 million (~US \$66,667) annually.

It was only in 1984 that Taiwan first began construction of sanitary landfills, and not until 1991 did construction of the first incinerators begin (Houng, 2012). Today, 21 government-owned and 3 privately-owned WtE incinerators treat approximately 20,000 tons of MSW daily, generating 8 million kWh/day of electricity. All 150 incinerators in Taiwan are gradually being transformed into regional biomass energy centers (TEPA, 2011). The remaining landfills are being shut down after reaching capacity, and future byproducts of incinerators will be used for land reclamation (Houng, 2012). Dr. Houng, Waste Management Advisor to TEPA, states that TEPA tests landfills and has more stringent liner requirements than the U.S., and over the next 5-7 years, the 62 to 67 landfills left, ranging 50-200 acres in size, will only be used for burying incinerator ash.

The top three types of WtE incinerator plant wastes by volume were coal ash, blast furnace slags, and electric arc smelting furnace slag, comprising 55.3% of all reported wastes. Research is being conducted by universities and start-ups on the practical applications of these wastes in construction and other infrastructural uses, but more information is needed before policies on next generation WtE plants can be developed (Shen, 2012).



Currently, the dominant service provider operating Taiwan's WtE plants is France's Veolia. Through the joint venture of its sole subsidiary VES Energy Recovery Taiwan Co., Ltd. With Taiwan Cement Corp., Onyx Ta-Ho Environmental Services Co., Ltd. operates six WtE plants and three energy-from-landfill gas (Veolia East Asia, 2012).

Swire SITA Waste Services Ltd. In Taiwan, also has a presence, through a 50/50 joint venture between UK's Swire Group and Frances' SITA. Its first WtE plant in Taiwan was built in 2000, in Kaohsiung, for a term of 20 years, and processes 1,350 tons of IW and MSW, producing 27 mWh/day to Taipower (Taiwan Power Company, state-owned ESCO) (Swire Pacific, 2000). Moving forward, Swire SITA Taiwan is interested in the landfill land reclamation segment of the SMM business.

Taiwan's SMM policies have transformed from earlier "end-of-pipe treatment" to the current "zero-waste" mechanisms, and rates continue to improve by adhering to strategically progressing through step-by-step measures for "source reduction" and "resource recycling and reuse." However, Taiwan's achievements in waste recycling are resulting in over-supply of WtE incinerator capacity, and private operators of WtE plants, who won contracts based on low bids, are seeking other feedstock to replace high-calorific waste like plastic and tires being recycled out of the waste stream. Treatment of hazardous wastes (HW) needs to improve as well; latest numbers from TEPA indicate that in 2010, the top three types by volume are: electric arc smelting furnace ash (26%, or 229,500 tons), copper sludge (14%, or 126,700 tons), and waste solution (12%, or 112,000 tons).

TEPA proactively evaluates what can be done to retrofit current mass burn incinerators to improve combined heat and power (CHP) energy returns, as contract terms near their end. PAG is one of the top technologies under consideration. Recouping

challenging materials resulting from improved recycling, such as copper, are another area TEPA and MOEA are evaluating. According to TEPA officials, the former models of Build-Operate-Transfer or Build-Operate-Own (BOT or BOO) are also under evaluation. Training and certification programs of SMM professionals will continue to be expanded (Shen, 2012).

#### Controlling Epidemiological Costs – The Promise of Plasma Arc Gasification (PAG)

The age-old garbage remedy, using fire to decrease garbage, today takes the form of incineration utility plants, which incinerate garbage to get energy in the form of electricity, heat, or steam, or create a combustible fuel, such as methane, methanol, or ethanol. Due to the heterogeneous nature of solid waste, commonly containing plastics and heavy metals, incineration processes emit toxic emissions that cause acute illnesses and chronic diseases in living systems. Vulnerable human subpopulations such as pregnant women, fetuses, children, the elderly, are particularly susceptible to risk of harm. Ecosystems and food chains biomagnify environmental toxicity, creating multiple pathways of harm to humans, animals, and plants. The effect upon bacteria, fungus, and other simple-celled organisms is also unknown. Comprehensive analysis of international epidemiological studies from 1965 to 2012 on health consequences from E-waste exposure have concluded that the multiple vector entryways into ecosystems and living organisms is unprecedented in complexity and scale, and initial studies strongly indicate the increased risks of epigenetic harm (Grant, et al., 2013).

Waste processing incineration facilities control emissions of dioxins, furans, particulate matter (PM), heavy metals, by using lime scrubbers, electro-static precipitators,

fabric filters, and other catalyst or reactor mechanisms to capture, destroy, or clean the smoke of pollutants before releasing into the air. New facilities of waste-to-energy (WtE) plants employ combinations of these technologies to meet regulatory requirements. WtE plant construction costs are utility-scale, and construction costs range from double- to triple-digit millions of dollars. Municipalities often manage solid waste by simply exporting it overseas, instead of investing in home-based facilities to process their own waste (Niessen, 2010; Rogoff & Screve, 2011; Li & Wang, 2012).

Overseas locations receiving E-waste and other solid waste often do not even have older generation incineration facilities, and workers simply resort to open-air burning, releasing toxic fumes and PM that carries over air, settles into water and soil, entering living organisms. The health and ecosystem risks can be decreased by using newest available thermal processing technology that can be scaled down from utility-scale to a mobile size.

One of the newer WtE technologies – plasma arc gasification (PAG) – is actually an old technology that has been used in the steel industry in the late 1800s. Blast furnaces were used over 180 years ago in Europe to produce “producer gas”, which was used to produce heat, steam, or hot water, and then electricity (Mukand Limited, 2011).

Later, the chemical industry in the early 1900s used plasma to manufacture acetylene fuel from natural gas. This chemical industry application remains the largest (150 megawatt) plasma heated industrial plant in the world, in Germany (Solena Group, 2015). Industrial applications of thermal plasma include: cutting, welding, spraying, metallurgy, mass spectroscopy, nano-sized particle synthesis, powder spheroidization, and hazardous waste treatment of air pollutant control residues, radioactive wastes and medical

waste. The range of applications indicates the flexibility of plasma technology. The attractiveness of the technology is the near absence of  $O_2$  in the thermal plasma furnace, thereby avoiding emissions of  $NO_x$ ,  $N_2O$ ,  $SO_x$ ,  $CO$ , PCDD/F (dioxins and furans) (Byun, Cho, Hwang, & Chung, 2012; Astrup, Tonini, Turconi, & Boldrin, 2014).

Gasification is a thermo-chemical process using plasma, converting feedstock into a combustible producer gas. Plasma is considered the “fourth state of matter,” and is a gas that is highly ionized (electrically charged) and very high temperature, capable of conducting electrical current. Lightning is a natural form of plasma, as is the gaseous surface of the sun. Man-made plasma is created by passing an electrical discharge through a gas such as air, oxygen, nitrogen, argon, and others, within a plasma torch. The electric arc interacts with the gas, causing the temperature to increase nearly as hot as the sun’s surface, disassociating it into electrons and ions. Molecular constituents, including hydrogen and carbon monoxide, the two building blocks of syngas, are produced. In a “combined cycle” application, syngas from the gasifier is then cleaned up to a specification comparable to natural gas, and burned in the absence of oxygen to create power. The absence of oxygen makes the emissions from this type of combined cycle power plant as low as or lower than a comparable natural gas fired power plant.

Westinghouse Plasma Corporation’s gasification technology was developed over 30 years ago in collaboration with NASA to simulate space re-entry conditions over 10,000°F. In the 1980’s, the technology was further developed to process hazardous wastes, and in cooperation with Hitachi Metals, a pilot scale 24 ton/day gasification plant was established in Yoshii, Japan. Westinghouse is now owned by AlterNRG in Canada (AlterNRG, 2014), and is considered the most established gasification technology

globally. AlterNRG emission controls result in significantly cleaner emissions than existing incineration and regulated standards (Niessen, 2010).

Modern gasification technology is thermally-based, but distinct from traditional incineration plants. The distinction is primarily that thermal conversion processes are characterized by higher temperatures and conversion rates than biochemical processes. These technologies contain a continuum of processes ranging from thermal decomposition in a primarily oxygen starved environment (commonly referred to as pyrolysis/cracking processes) to partial oxidation in a sub-stoichiometric environment (or gasification processes) (U.S. Environmental Protection Agency, 2012). Gasification technology can convert any carbon-based material into water, carbon monoxide, hydrogen, and methane, forming a synthetic natural gas (syngas), which can then be converted into energy forms such as electricity, steam, or ethanol (AlterNRG, 2014). Emerging waste conversion technologies operate on commercial or demonstration scales in Australia, Canada, Europe, and Japan, using pyrolysis, plasma arc and microwave gasification.

However, the problem with on-site E-waste processing is that developing economy municipalities lack financial resources to acquire modern cutting-edge utility-scale plants that can efficiently convert myriad solid waste into energy. Additionally, the dumps aren't usually located where municipalities might prefer to build long-term, utility-scale WtE plants. Currently, utility-scale WtE plants require an average capital investment of USD \$420 million and average annual operating costs of USD \$22 million. Despite some researchers' estimates of USD \$22 million returns from electricity sales, reliable data is hard to come by, as plant operators self-report, and no standardized reporting methodology exists, due to the concurrent development of new gasification

technologies all still in demonstration stage.

The only technology provider with the most established commercial facilities, as well as the largest renewable energy facility in the world, is AlterNRG's Westinghouse Plasma Corp. Gasification Technology. AlterNRG's integrated plasma gasification combined cycle facility (IPGCC) includes a typical solid waste management facility that could process 1,000 tons/day of solid waste, with the addition of the plasma arc gasifier unit, producing around 50 MW of power (AlterNRG, 2014). In addition to utility-scale installments, this technology can also be used in micro-scale applications, and NASA is currently exploring PAG applications in low earth orbit spaceflight, for power generation and syngas production (NASA, 2015).

AlterNRG's gasifier torches come in four sizes and can process feedstock of any composition. According to AlterNRG publicly available literature, this allows for a range of flexibility in applications, particularly for smaller than utility-scale plants, micro-grid applications, and smaller more specialized applications. The syngas produced can be used as feedstock in other processes to produce electricity, steam, (Figure 15, Page 67) or fuels including diesel, ethanol, jet, methanol, propanol of varying power (Table 4, Table 5).

Table 4. AlterNRG capacity and dimensions of plasma gasifiers (AlterNRG, 2015)

Gasifier Model	Feedstock	Capacity (tpd)				Syngas Produced (Nm <sup>3</sup> /hr)	Dimensions (meters)		
		Air Blown		Oxygen Blown			Top Dia.	Bottom Dia.	Vessel Height
		Low	High	Low	High				
G65	MSW	540	620	1000	1000	65,000	9	4	24
	Haz Waste	430	720	830	1000				
W15	MSW	120	140	240	290	15,000	6	2.5	15
	Haz Waste	100	160	190	300				
P5	MSW	40	50	80	100	5,000	4	2	10
	Haz Waste	30	50	60	100				

Table 5. AlterNRG energy production output from gasification plant processing MSW (AlterNRG, 2015)

Gasifier Model	Capacity (tpd of MSW)	Syngas Produced (NM <sup>3</sup> /hr)	Syngas Chemical Energy, HHV (GJ/yr)	Combined Cycle Power Plant (MW gross/net)	FT Liquids BPD / BPY	Fossil Fuel Replacement (bbls/year)
G65	1000	65,000	4,100,000	58 / 39	785 / 287,000	670,000
W15	290	15,000	976,000	14 / 9	188 / 68,000	160,000
P5	100	5,000	323,000	4.5 / 3	62 / 23,000	50,000

## Research Question and Hypotheses

This study hypothesized decreasing elementary manual E-waste dismantling in China would directly contribute to improving human health outcomes for the most at-risk populations in China, led by Guiyu, thereby assuming decreasing overall greenhouse gas (GHG) emissions impacting the globe. In order to move towards this goal, this study examined Taiwan's Smart Materials Management (SMM) system as a promising solution to localize to China's biggest E-waste dismantling region, Guiyu. China's reliance upon coal for electricity exacerbates GHG emissions. It was hypothesized that decreasing mechanical shredding to access printed circuit boards (the first major step of E-waste dismantling) would directly contribute to lessening GHGs and improving health outcomes. If E-waste flows are controlled, then using plasma arc gasification to process the waste into energy can become more attractive to traditional financing, facilitating human and ecological health improvement.

In order to evaluate the feasibility of this hypothesis, the goals of this study focused upon: surveying research studies examining epidemiological toxicity of E-waste; determining a life cycle analysis (LCIA) baseline for the first step in elementary E-waste dismantling (mechanical shredding) in China compared to the rest of the world; and examining Taiwan's SMM system in order to control the flow of printed circuit boards away from illegal enterprises to licensed processors; and selecting the best plasma arc gasification system.

This study hypothesized that focusing upon the dismantling stage of E-waste



printed circuit boards (PCBs) would be most beneficial because of both prevalence and value: every electronics product contains one, and every PCB contains valuable metals.

This study focuses on the LCIA of the mechanical shredding step because it is the first step after initial manual dismantling, and the first significant cause of airborne toxic and hazardous particulate matter (PM), resulting from mechanical shredding.

SimaPro 8.0.5.13 and the Ecoinvent 3 database were used to conduct the LCIA on 1 kg of heterogeneous E-waste, using ReCiPe Endpoint (H) V1.12 / Europe ReCiPe H/A method.

The variable focused upon was electricity use in China as compared to the rest of the world, due to the fact that 83% of China's electricity is generated using greenhouse gas emitting coal (Song, Wang, Li, & Zeng, 2013).

This study further hypothesized that the most efficient method of reducing GHG emissions, epidemiological risks, and local waterway ecology damage was to shift the focus away from the low value of rudimentary metals recovery from PCBs.

Instead, it was hypothesized that greater benefit would be found reducing E-waste open air dumps by rapid conversion into reusable energy. This study hypothesized employed peer-reviewed literature surveys of Taiwan's SMM, global research of epidemiological impacts from E-waste processing, and LCIA studies of E-waste processing, as well as evaluating publicly-available literature of plasma arc gasification systems, to determine a policy-based approach that could be localized to Guiyu's context.

The waste-to-energy technology focused upon was plasma arc gasification torches manufactured by industry leader AlterNRG, which holds the original Westinghouse patents on technology used by NASA.

## Chapter II

### Methods

An internal-level, allocation, recycled content life cycle assessment of heterogenous E-waste, using ReCiPe endpoint method, was conducted using SimaPro v8 and Ecoinvent v3. It was assumed that this data could be extrapolated to establish an estimated baseline to substitute for unavailable PCB. The ecoinvent database included an assessed list of material and fuel inputs for 1 KG of PCBs (Table 6).

Table 6. Material inputs from the technosphere for 1 Kg of PCBs.

Materials/fuels	Value	Unit	Distribution	CV
Mechanical treatment facility, waste electric and electronic equipment {GLO}  market for   Alloc Rec, U	8E-10	P	Lognormal	4.3722
Electricity, medium voltage {CN}  market for   Alloc Rec, U	0.066	kWh	Lognormal	1.3203
Lead	0.0413	Kg	Lognormal	1.7488
Iron	0.483	Kg	Lognormal	1.7488
Bromine	0.0238	Kg	Lognormal	1.7488
Nickel	0.0161	Kg	Lognormal	1.7488
PET	0.01	Kg	Lognormal	1.7488
Phosphorus	0.0014	Kg	Lognormal	1.7488
Polychlorinated biphenyls	0.000189	Kg	Lognormal	2.215
Tin	0.0301	Kg	Lognormal	1.7488
Antimony	0.0119	Kg	Lognormal	1.7488
Cadmium	0.00238	Kg	Lognormal	1.7488
Copper	0.042	Kg	Lognormal	1.7488
Chlorine	0.07	Kg	Lognormal	1.7488
Chromium	0.00518	Kg	Lognormal	1.7488
Aluminium	0.04	Kg	Lognormal	1.7488
Zinc	0.1309	Kg	Lognormal	1.7488
Mercury	0.0011119	Kg	Lognormal	1.7488

“PCB” is used in lieu of printed wiring board (“PWB”) because the elementary methods of informal dismantling employed in China typically involve manual removal of PWB components (e.g. resistors, capacitors, copper coils, others), and the remaining PCB is mechanically shredded, or alternatively, melted over an open flame (Song, Wang, Li, & Zeng, 2013). The various mechanical means of breaking PCBs down to small sizes is beyond the scope of this study, but researchers have found that mechanical shredding down to a fractional size of 6 mm or smaller is most effective for liberating copper and other metals. Milling below 150  $\mu\text{m}$ , no interlocking of metallic and non-metallic particles is achieved, however, the fine dust resulting from this operation is extremely difficult to manage (Li, Shrivastava, Gao, & Zhang, 2004; Ghosh, Ghosh, Parhi, Mukherjee, & Mishra, 2015).

Information about Taiwan’s SMM system was acquired directly from the source of the data, Taiwan’s EPA researchers, as provided by the Minister of the Environmental Protection Agency of Taiwan to the author.

Due to challenges acquiring proprietary, and often unavailable, plasma arc gasification data as applied to E-waste scenarios, lack of access to China’s E-waste facilities or lab resources needed to test E-waste, this study used publicly available peer-reviewed scientific literature, and all extrapolations are duly noted. The plasma arc torch selected for this study is manufactured by AlterNRG (Canada), which owns the original Westinghouse patents developed for NASA applications (AlterNRG, 2015).

The concept of a modular plasma arc gasification (PAG) system was developed by the author and Professor Ramon Pina Sanchez, in 2011, Cambridge, MA as part of another paper related to this study. NASA is currently studying the possibility of a

micro-scale PAG system for use on space shuttles (NASA, 2015).

Selected literature used for human health risk assessment all contained documentation of how systematic reviews were conducted to collect the data presented. Human health risk assessment data were extracted from thorough studies that applied 2009 PRISMA guidelines, and evidence of the causal association between E-waste exposure and human health outcomes was assessed within the Bradford Hill framework (Grant, et al., 2013).

This study assumed, based upon Ecoinvent v3 dataset system description comments, that:

- Because waste PCBs account for ~3% of nearly 50 Mt/year global E-waste streams, and contain highly desirable metals (e.g. one ton of PCBs yields ~284 g. of gold), conducting a life cycle assessment (LCIA) of the “mechanical shredding” step of heterogeneous E-waste as a whole can substitute for the unavailable data on shredding of PCB E-waste; and mechanical shredding in China’s E-waste micro-workshops are typically conducted in the open air with no safety mechanisms or protective equipment; and
- Because the first significant cause of airborne toxic and hazardous particulate matter (PM) is from the mechanical shredding step, that this first step should be under controlled facility conditions to decrease human health risks resulting from this E-waste step.
- The next step, dissolving and separating metals from plastics of shredded PCB, was eliminated from consideration herein because several experimental methodologies are currently being tested at metallurgical labs of multinational

corporations, and that data is pending.

The scope of this study required limiting the examined markets to just Guiyu, China. This hypothesis takes into account the lack of renewable energy credits, physical logistics, avoiding long-distance waste transfer, and local economics. For example, the economics of waste management in Singapore, Hong Kong, Hawaii, and Japan will likely be distinct from those of Africa, Brazil, or Mexico, which will again be distinct from the Middle East, China, or India. The overarching challenges to this study are the significant inconsistencies of non-standardized data sources in each area considered below.

#### Life Cycle Assessment, ReCiPe Endpoint Method of Shredding Heterogenous E-waste

An examination of a comprehensive literature survey study of life cycle assessments of waste-to-energy technologies was conducted (Astrup, Tonini, Turconi, & Boldrin, 2014).

SimaPro 8.0.5.13 and the Ecoinvent 3 database were used to conduct the LCIA on 1 kg of heterogenous E-waste, using ReCiPe Endpoint (H) V1.12 / Europe ReCiPe H/A method. An “internal-level, allocation, recycled content” life cycle assessment of “heterogenous E-waste”, using ReCiPe endpoint method, was conducted using SimaPro v8 and Ecoinvent v3. It was assumed that this data could be extrapolated to establish an estimated baseline to substitute for unavailable PCB data (Song, Wang, Li, & Zeng, 2013).

#### Smart Materials Management (SMM) System Deployed in Taiwan

Information about Taiwan’s SMM system was acquired directly from the source of the data, Taiwan’s EPA researchers, as provided by the Minister of the Environmental

Protection Agency of Taiwan to the author.

#### Best Available Technology: Modular Plasma Arc Gasification (PAG)

Due to challenges acquiring proprietary, and often unavailable, plasma arc gasification data as applied to E-waste scenarios, lack of access to China's E-waste facilities or lab resources needed to test E-waste, this study used publicly available peer-reviewed scientific literature, and all extrapolations are duly noted (AlterNRG, 2015). Assumptions were made by the author.

#### Risk Assessment: Human Health Risks Using Epidemiological Data

An examination of a comprehensive literature survey study of health consequences of exposure to E-waste was conducted (Grant, et al., 2013).

Selected literature used for human health risk assessment all contained documentation of how systematic reviews were conducted to collect the data presented. Human health risk assessment data were extracted from thorough studies that applied 2009 PRISMA guidelines, and evidence of the causal association between E-waste exposure and human health outcomes was assessed within the Bradford Hill framework (Wang, Kuehr, Ahlquist, & Li, 2013; Grant, et al., 2013; Song Q. L., 2014).

#### Goal and Scope

Intended application was the shredding of various mixed E-waste. The reason for carrying out this LCIA was to understand the environmental and human health impacts of mechanical shredding E-waste in China as compared to the rest of the world (RoW).

The target audience is “internal study”, or a high-level snapshot comparison of shredding processes in different markets. The functional unit was one kilogram of E-waste.

### System Boundaries

Process focus was upon the mechanical shredding of the input of one kilogram of E-waste using medium voltage electricity, producing shredded fractions of E-waste. The LCIA first compared 1 Kg of E-waste recycled (functional unit) in China and the rest of the world until the material is ready for final disposal. This served as a baseline of business as usual practices globally, then activities will be compared between a regular landfill disposal and a plasma incinerator. Included activities were: mechanical treatment infrastructure, energy consumption, emissions to air, and an estimation of the efforts for transportation. The technology level was 3 Current (a default setting) and the technology used was: modern shredder facility with 2 shredders, 2 magnetic separation, and 2 Eddy-current separation steps, all connected by conveyor belts. Disposal activities considered were open dumps in China (BAU), a landfill in China (intermediate option) and a plasma incinerator (Best Available Technology- BAT).

All other processes were excluded: human activities, R&D, services. The data used was from the Ecoinvent 3 European study, and values were used for global averaging data.

### Key Assumptions and Limitations

The data used, “known inputs from the technosphere (materials/fuels)” are listed in the Appendix. Since no China-specific data is yet available, the secondary data

source, Ecoinvent data from a Swiss study of E-waste shredding, was substituted. Twelve material inputs were included.

#### Research Limitations of Best Available Technology, PAG

Modular self-contained wastewater treatment systems and solar panel array systems have already been successfully patented and publicly-listed, such as Ecosphere Technologies' Ozonix and the Ecos PowerCube respectively. Electricity generation can be created anywhere the standard 10', 20' or 40' ISO shipping containers can be located (Ecosphere Technologies Inc., 2014). It is hypothesized that the proposed modular PAG system can be similarly sized to fit in standard ISO shipping containers.

The feasibility of a self-contained, portable system is hypothesized to be best suited for converting open-air E-waste dumps into marketable energy products in developing countries.

Plasma arc gasification technology as provided by AlterNRG is selected for analysis at this point due to its superior conversion capabilities of the broadest range of municipal solid waste as raw feedstock for energy generation. However, this is also an assumption based upon industry self-reported data.

The nature of the technology inherently produces engineering and material challenges, which is a central challenge to this study. The lifespan of the proposed PAG units hinge upon the durability of the material parts to withstand any inputted material and extreme temperatures. Modern gasification technology thermal conversion processes are characterized by much higher temperatures (up to 2,912°F) than biochemical processes, and the continuum of processes range from thermal decomposition in a primarily oxygen



starved environment (pyrolysis/cracking) to partial oxidation in a sub-stoichiometric environment (gasification) (U.S. Environmental Protection Agency, 2012). As a result, gasification technology is of strong investor interest due to its unique, almost magical ability to convert, with negligible micro-emissions, any carbon-based material into water, carbon monoxide, hydrogen, and methane, forming a synthetic natural gas (syngas), which can be readily converted into energy forms such as electricity, steam, or ethanol. Any inert glass and metals are contained in the resultant “slag” which can be further processed for metals and sold, or sold as a superior concrete substitute (AlterNRG, 2014).

#### Research Limitations of Market Conditions

Limitations of this research project centers around access to best available, reliable data for both the PAG and cargo container/transport technology, as well as the market conditions. Since the proposed solution does not yet exist on the market, projections must be based upon data as provided by technology providers and governmental agencies. There may be reluctance on the part of both of these stakeholders to provide the needed data, and some assumptions will be required for this thesis, affecting the results of this study.

Many waste management market opportunities exist in regions defined as megacities and tourism destinations. However, the market feasibility of this proposed solution hinges upon knowledge gaps stemming from two main factors:

- 1) The degree of municipalities’ cooperation with available social impact and waste supply elements, prior to the gasification step, including participation with the United Nations’ Clean Development Mechanism (CDM) (United Nations

Framework Convention on Climate Change, 2014), and

2) The existing limitations of the plasma arc gasification (PAG) technology itself, and new limitations presented by adapting the PAG technology into a “novel” modular format as proposed herein.

However, market prices may fluctuate at any time, eroding profits from a process that itself can rapidly deteriorate from regular operations. Despite these challenges, investments into emerging waste conversion technologies continue, operating on commercial or demonstration scales in Australia, Canada, Europe, and Japan, using pyrolysis, plasma arc and microwave gasification. Local politics affect market footholds at any time (particularly given corruption) of all of these nascent technologies.

Funding availability for startup costs also hinges on these factors, making any life-cycle assessments for the lifespan of a PAG unit more variable than preferred, and affecting the cost of money.

Currently, utility-scale WtE plants require an average capital investment of US\$420 million and average annual operating costs of US\$22 million. The factors above directly impact the cost estimations of the proposed PAG unit. The volume, composition, and consistent delivery of waste to the PAG units have traditionally been a limiting factor to researchers’ estimates of success of utility-scale gasification units. With this study, efficiently finding open air dumps can help municipalities better plan limited resource expenditures.

Smaller dumps, such as those containing biowaste or chemical waste, can be even more toxic and are just as important in locating as the larger heterogenous dumps. Municipalities need to locate dumps and stop open air burning, as well as address the

needs of informal workers who sort recyclables at dumps. Recently, efforts have been made to develop remote-sensing technology to improve upon past efforts at detecting dumps, which relied upon aerial photographs or satellite imagery. New microsatellite technology has helped municipalities both locate and analyze the composition of the growing number of open-air dumps (Yalana, 2014). But often it is small dumps that are the most toxic yet difficult to find and therefore just as epidemiologically important.

## Chapter III

### Results

The focus of this study's LCIA was upon the first stage of major dismantling emissions – mechanical shredding, comparing China to the rest of the world (or GLO, global) – using method of ReCiPe Endpoint, confidence interval of 95%. This analysis was based upon Swiss data over 10 years old, and technical details about the shredders were unavailable.

#### Life-Cycle Inventory Assessment of Shredding Heterogenous Mixed E-waste

##### Results of LCIA – WEEE Shredding, Global V China: Electricity Variable

The comparison between business-as-usual (BAU) E-waste operations in China and the rest of the world show that Chinese processing and shredding of PCBs produces 30% more overall environmental damage than average processing and shredding operations of PCBs in the rest of the world (or global, GLO, in the figures) (Figure 6). GLO represents the entire rest of the world as measured by Ecoinvent.

It includes activities considered to be a valid average of all the countries in the world. GLO represents the entire rest of the world as measured by Ecoinvent.

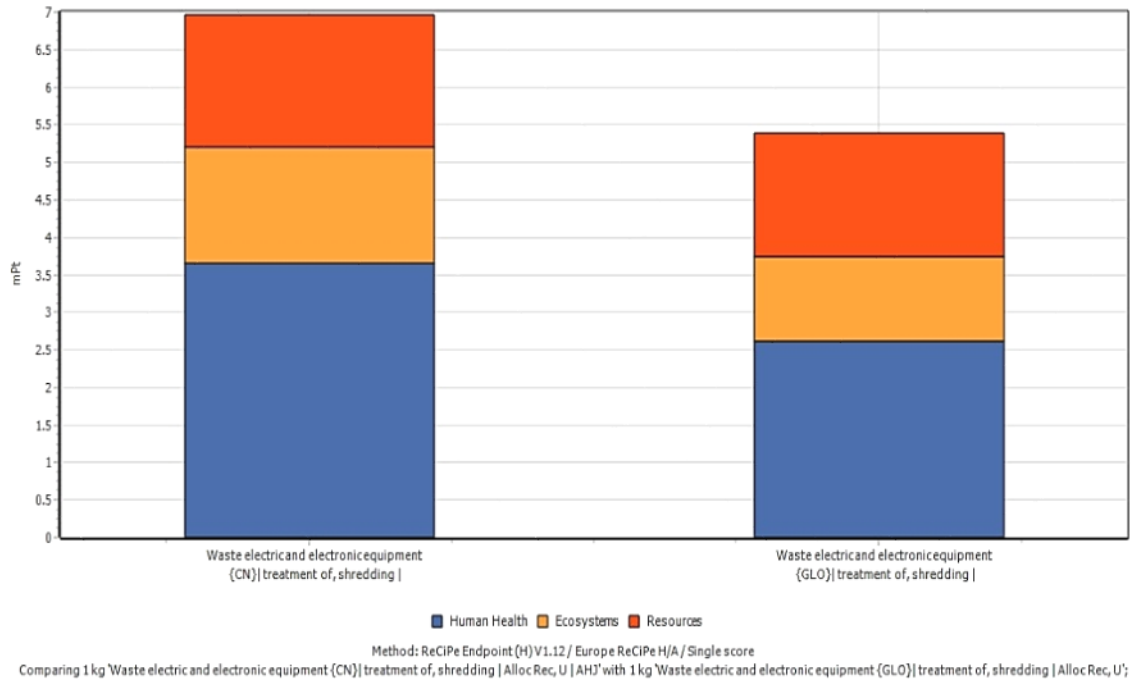


Figure 6. Comparison of BAU operations to dispose of 1 Kg of E-waste in China versus rest of the world.

The comparison between business-as-usual (BAU) E-waste operations in China and the rest of the world show that Chinese processing and shredding of PCBs results in damage to human health that is on average 30% higher than resource damage and ecosystem damage (Figure 7).

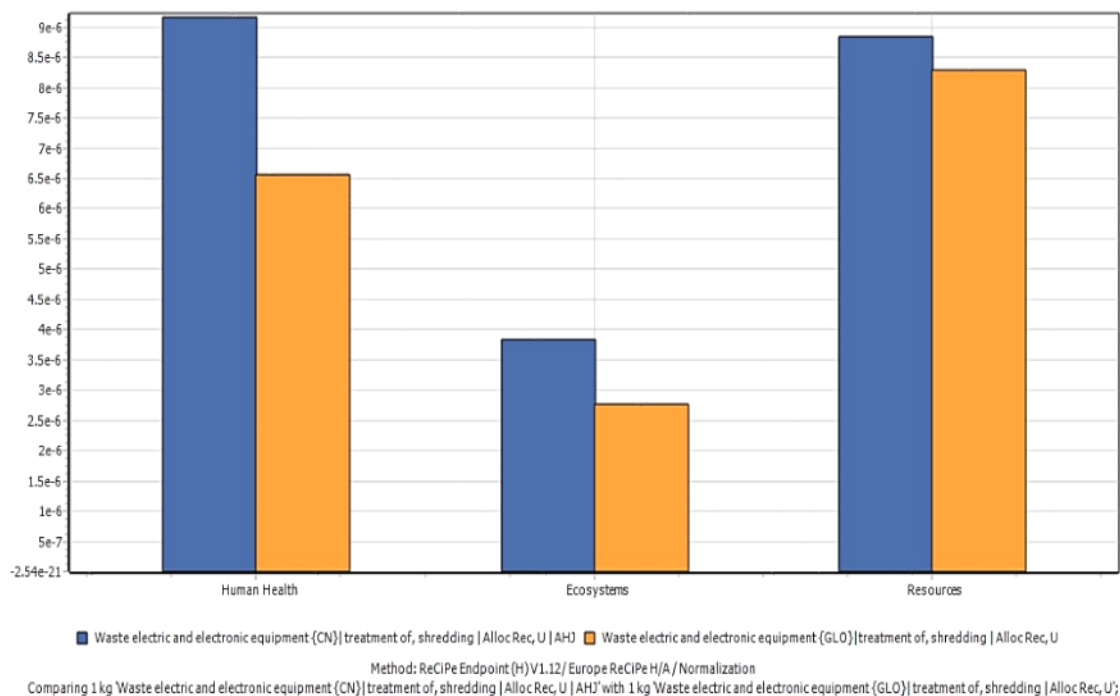


Figure 7. Human health, ecosystems, and resource damage of BAU operations to dispose of 1 Kg of E-waste in China versus rest of the world.

The LCIA single-score of 3 (Figure 8) provides a comparison against which to evaluate the certainty of results for other indicators (Figure 9; Figure 16, Figure 17, Appendix).

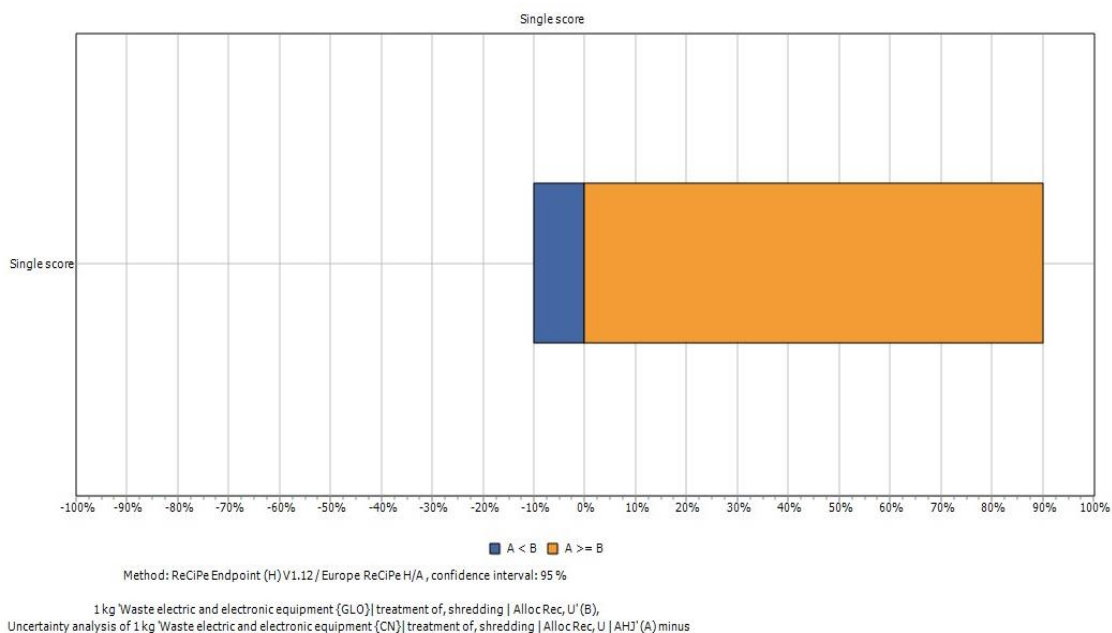


Figure 8. LCIA single-score of 3 is 90% weighted on cross-indicator damage in China's BAC methods of E-waste dismantling.

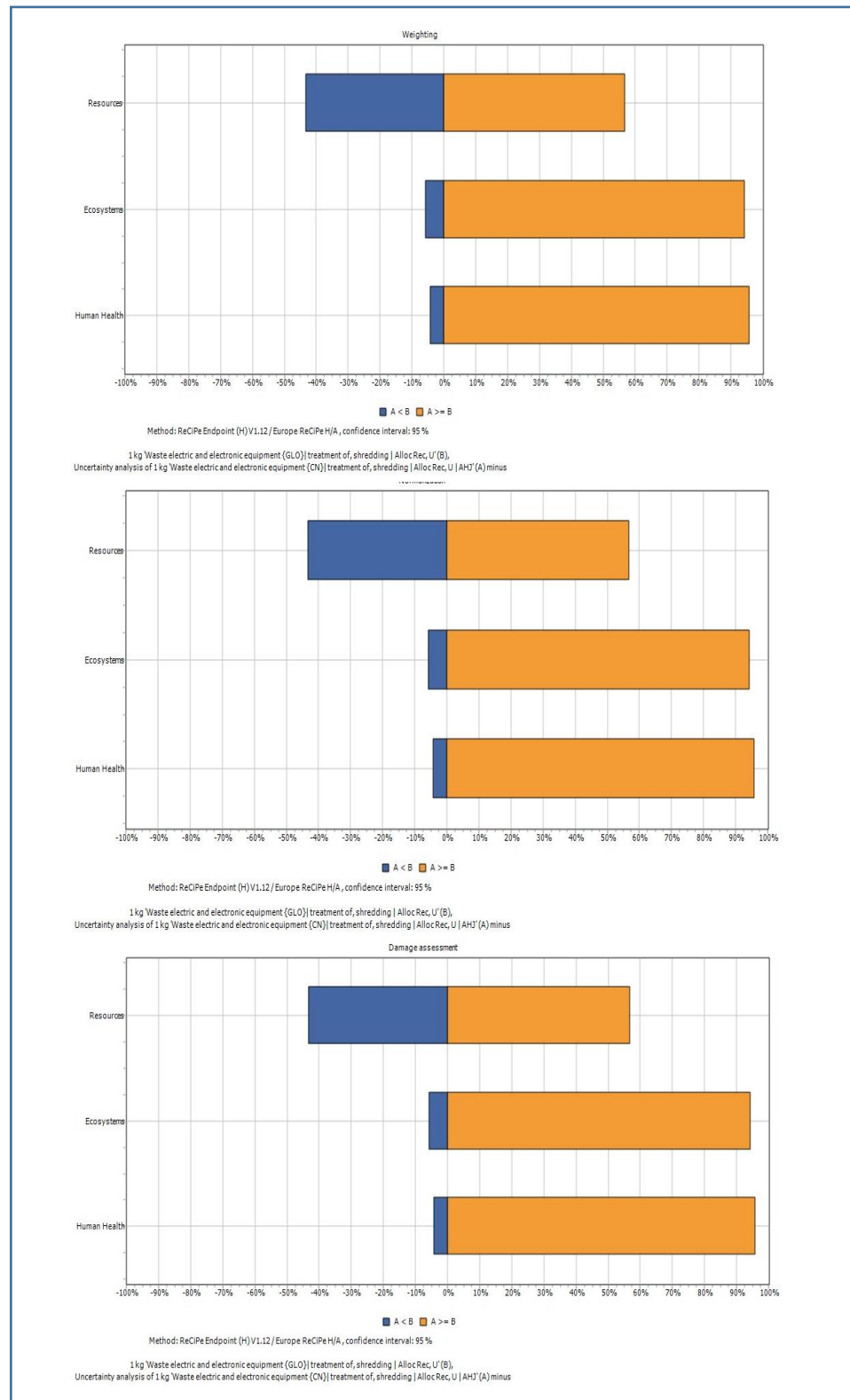


Figure 9. Uncertainty analyses comparisons show closely similar results.

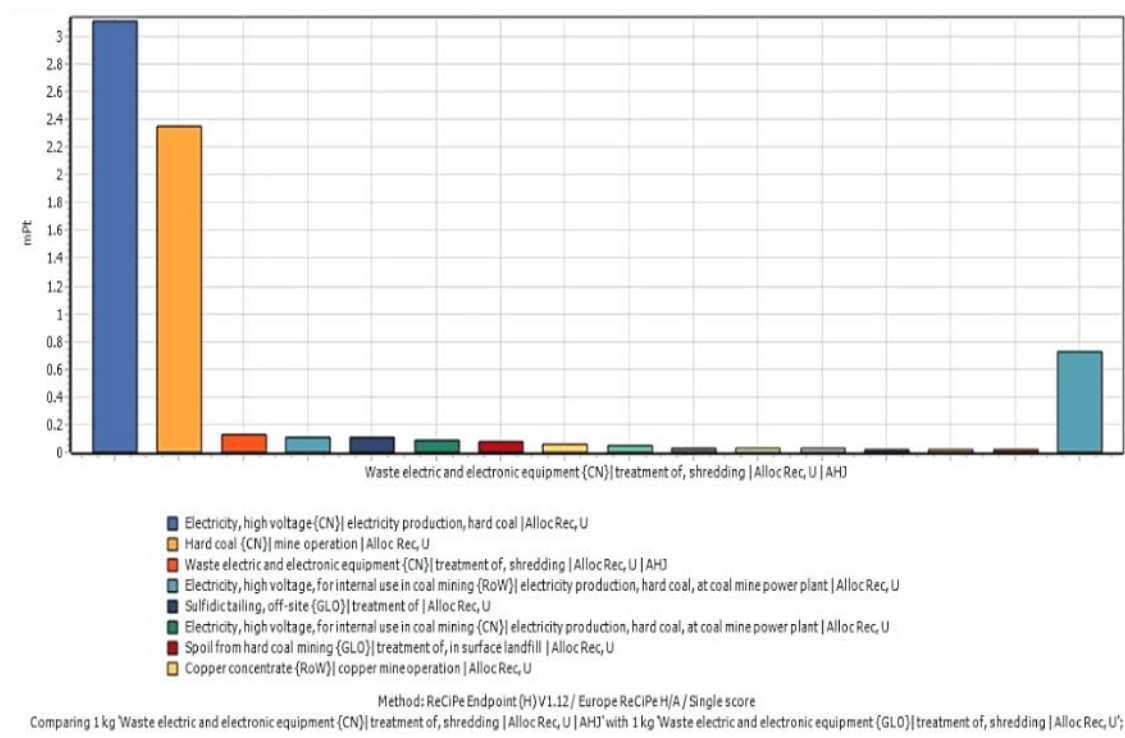


Figure 10. LCIA single-score results: shredding of E-waste in China resulting from coal-generated electricity and coal-mining operations (graph view).

Electricity from coal fired power plants, coal extraction and energy used for coal extraction are the biggest contributors to human health and environmental damages from shredding and processing of PCBs in China with more than 75% of the damage (Figure 10, Figure 11). This shows that the high reliance of coal electricity in China produces quantifiable environmental differences when compared to the energy mix used in the rest of the world, which translate in a more environmentally-friendly BAU shredding and processing of PCBs in the rest of the world. Up to this point the process was the same for the three disposal scenarios, these environmental damages are included in the overall damages of each disposal operation. This is important because approximately 66 KWh of electricity are needed to process and recycle 1 metric ton of electronic waste in China using the regular BAU option.



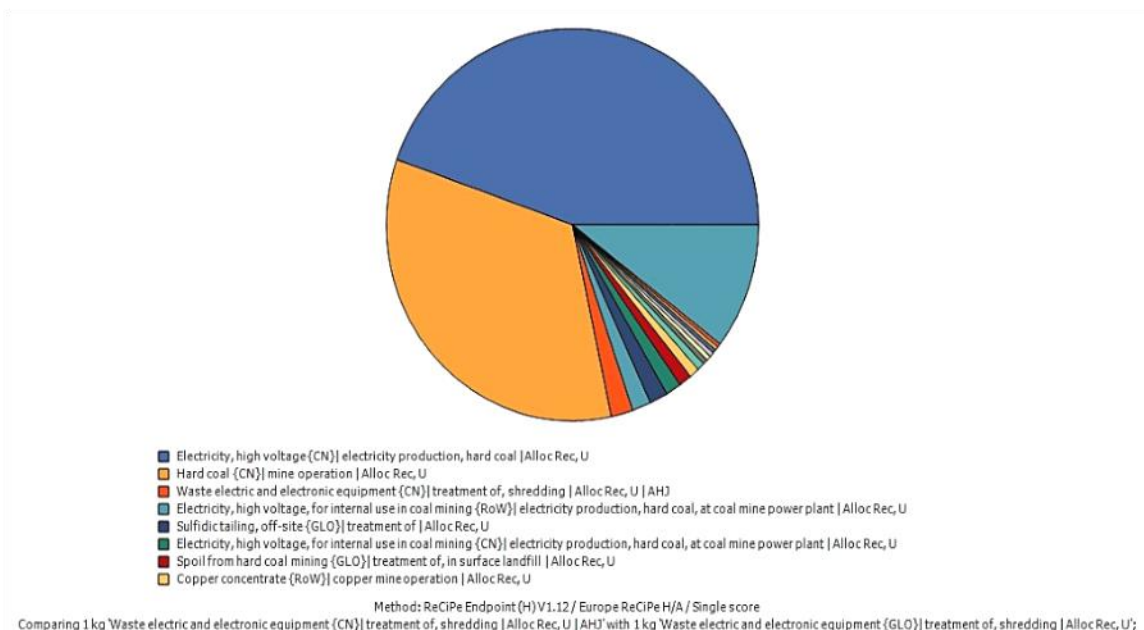


Figure 11. LCIA single-score results: shredding of E-waste in China resulting from coal-generated electricity and coal-mining operations (pie chart view).

The overall output of using E-waste to produce electricity in a regular low temperature incinerator (2200°F or 1200°C) is 484 KWh produced per ton of electronic waste, the ash for this process is rich in metals that can be recycled, but some dioxins and particulate matter are emitted to the atmosphere which might produce adverse health effects. The overall output of using E-waste to produce electricity in a plasma incinerator (8000°F or 4500 °C) is 764 KWh produced per ton of electronic waste used, the vitrified waste of this process is rich in metals that can be recycled, there are no dioxins and minimum particulate matter emitted to the atmosphere, therefore there are very little adverse health effects caused by air pollution from this process. Overall a plasma incinerator reduces overall adverse impacts by 364% and the regular incinerator also reduces overall adverse impacts by 240% compared to regular BAU E-waste disposal practices in China (Figure 12).

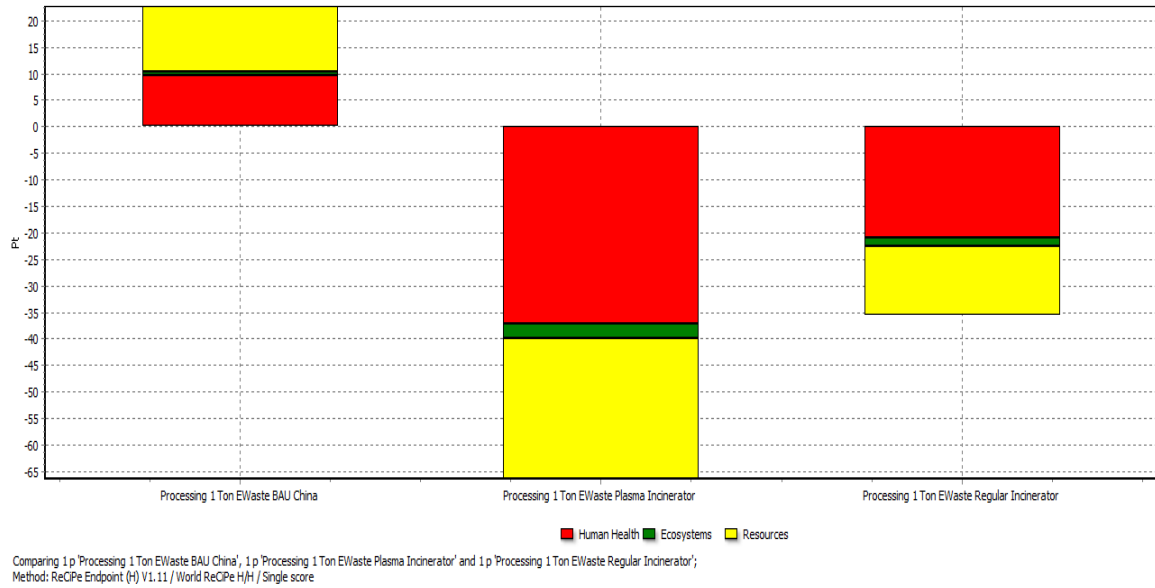


Figure 12. Comparison of overall environmental impacts. 1 metric ton of regular E-waste disposal, plasma incineration and regular low temperature incineration

The biggest benefits came from reduction of human health damages, followed by reduction in resource depletion damages and then ecosystem damages (Figure 13).

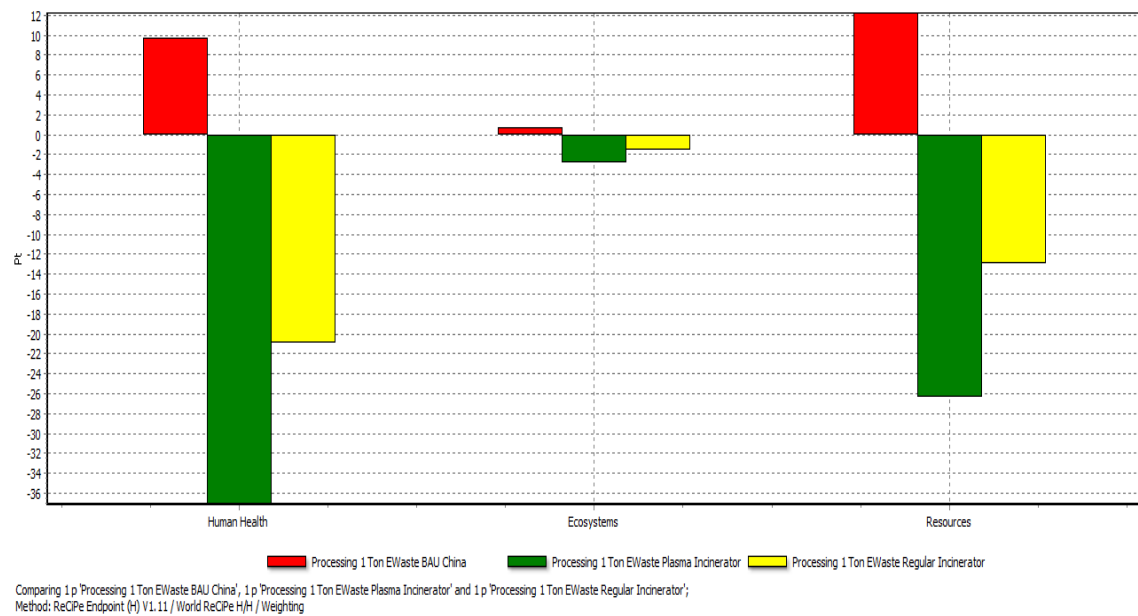


Figure 13. Normalized human health, ecosystem, and resources damages (1 ton E-waste)

These benefits are driven by a significant reduction in particulate matter and toxic emissions due to generation of low emissions electricity that substitute energy produced with a high content of fossil fuels that is distributed in China's national electric grid.

AlterNRG's Integrated Plasma Gasification Combined Cycle (IPCC) (Figure 14, Appendix) can significantly control PM emissions, resulting in emissions results superior to incineration and exceeding U.S. regulated standards (Table 7), which are currently more stringent than China's standards, which are currently unevenly enforced (Grant, et al., 2013).

Table 7. AlterNRG emission controls significantly cleaner than incineration and regulated standards (AlterNRG, 2015).

Pollutant	Units	AlterNRG Combined Cycle	Permitted Incineration Facilities (USA)	US EPA Section 111(d) Emissions Guidelines
Nitrogen Oxide (Nox)	ppmvd	36	110-205	205
Particulate Matter (PM)	mg/dscm	4	16-27	25-27
Sulfur Dioxide (SO <sup>2</sup> )	Ppmvd	1	26-29	29-31
Hydrogen Chloride (HCl)	Ppmvd	6	25-29	29-31
Carbon Monoxide (CO)	Ppmvd	19	100	100
Mercury (Hg)	µg/dscm	1	28-80	80
Dioxins, Furans (PCDD, PCDF)	ng/dscm	0	13-30	30-60

Greenhouse gas emissions in KgCO<sub>2</sub>eq are reduced by 487% by the plasma incinerator and by 319% by the regular low temperature incinerator (Table 8). Reductions of fine particulate matter (PM) and photochemical oxidant formation (smog) are the most significant contributors to the reduction of health risks, particularly in the areas near power plants in China. The majority of inhalable pollutants in Guiyu are of PM size 10 µg (smog) and 2.5 µg or smaller. The smaller the PM size, the greater risk to human health outcomes (Table 10, Appendix) (Grant, et al., 2013).

Processing 1-ton of E-waste by PAG process is far cleaner than other existing BAU methods employed in Guiyu, and other E-waste processing centers in China.

Table 8. Greenhouse gas and toxic emissions for three options of disposing of 1 metric ton of E-waste in China.

Impact category	Unit	Processing 1 Ton E-waste BAU China	Processing 1 Ton E-waste Plasma Incinerator	Processing 1 Ton E-waste Regular Incinerator
Climate change	kg CO <sub>2</sub> eq	197.3294	-764.5965	-433.1015
Ozone depletion	kg CFC-11 eq	0.0001	0.0001	0.0001
Terrestrial acidification	kg SO <sub>2</sub> eq	1.3308	-6.9854	-4.1607
Freshwater eutrophication	kg P eq	0.0153	-0.1216	-0.0733
Marine eutrophication	kg N eq	0.0501	-0.1239	-0.0618
Human toxicity	kg 1,4-DB eq	56.3916	-97.6248	-42.1675
Photochemical oxidant formation	kg NMVOC	1.5709	-2.0699	-0.8215
Particulate matter formation	kg PM <sub>10</sub> eq	0.4793	-2.1185	-1.2247
Terrestrial ecotoxicity	kg 1,4-DB eq	0.0279	0.0053	0.0134
Freshwater ecotoxicity	kg 1,4-DB eq	1.6603	-14.6782	-8.6596
Marine ecotoxicity	kg 1,4-DB eq	1.6471	-12.7750	-7.4598
Ionising radiation	kBq U235 eq	17.5389	-8.0763	0.7592
Agricultural land occupation	m <sup>2</sup> a	2.1185	-12.4103	-7.4785
Urban land occupation	m <sup>2</sup> a	3.2901	-4.8148	-2.1468
Natural land transformation	m <sup>2</sup>	0.0204	-0.0345	-0.0160
Water depletion	m <sup>3</sup>	1.0132	-3.3711	-1.8874
Metal depletion	kg Fe eq	7.2039	-9.1567	0.2834
Fossil depletion	kg oil eq	57.2354	-126.8909	-64.2579

## Chapter IV

### Discussion

This study employed peer-reviewed literature surveys of Taiwan's SMM, global research of epidemiological impacts from E-waste processing, and LCIA studies of E-waste processing, as well as evaluating publicly-available literature of plasma arc gasification systems.

This study found that the first major dismantling step of E-waste in China, mechanical shredding of PCBs, was also the first major source of GHG emissions. The dominant use of lignite coal, the most polluting, low-Btu coal combusted for electricity production in China, drives GHG emissions. The cost-benefit question was whether the epidemiological and ecological costs of rudimentary E-waste dismantling of PCBs to recover trace metals was worth the subsistence-level benefits perceived by Guiyu workers.

The first step of E-waste rudimentary dismantling, mechanical shredding of PCBs, is at least 30% less sustainable than the rest of the world. There was no data available about the types of shredding equipment used in Guiyu, nor was there consistent or complete data available in Ecoinvent or research literature surveyed. It was assumed that the equipment used in Guiyu is energy-intensive to operate, thus leading to greater GHG emissions and heavier human health and ecological impacts that would be reduced should this step be eliminated as currently employed.

The solution suggested in this study hypothesized that Taiwan's Smart Materials Management System could be profitably localized to Guiyu conditions, assuming other

socio-political controls remained fairly comparable. It was hypothesized the costs could be balanced only if the materials management system was complemented by a plasma-arc gasification facility to process open air dumps of E-waste, converting the relatively high-Btu plastics content to reusable energy. The plasma-arc technology selected was AlterNRG's Westinghouse-patented technology formerly developed for NASA's use.

There is a significant reduction in overall health and environmental impacts when using any of the waste incineration techniques, so they should be analyzed as some valid options to reduce human health and resource depletion damages from disposing of E-waste. Additionally, both options produce low emissions electricity and reduced solid waste, so they have an overall beneficial effect in the health and sustainability of the community.

Greenhouse gas emissions are reduced by any of the waste incineration techniques, this is caused by the substitution of electricity from the regular Chinese grid mix by using waste materials as sources of fuel for the gasification processes. Therefore, any of these technologies could be considered a climate change mitigation intervention which should be calculated to sell carbon credits in the Chinese market so future investments in infrastructure for advanced E-waste disposal will be easier to secure.

The major problem with E-waste is controlling its flows to less developed economies in the quest to extract the remaining value trapped within, rare elements and heavy metals, as well as usable energy gained from thermally converting plastics. Corporate producer responsibility for electronic products remains largely externalized to the environment (the commons) and to other human beings (Basel Action Network, 2011).

Policy needs to be developed in this area to facilitate business development of E-waste recycling, and control the long-term epidemiological and environmental costs. If externalized costs can be properly accounted to corporate producers, or even shared with consumers, not only can protection of the commons and human health be enabled, but properly authorized, licensed E-waste recycling businesses can also more easily flourish. Governments at all levels are considering better ways of measuring Gross Domestic Product, to include externalized costs and added value that the system still currently fails to account for (Stiglitz, Sen, & Fitoussi, 2010; Karabell, 2014; Coyle, 2014). The System of National Accounts approved by the United National Statistical Commission seeks to provide consistent, internationally accepted guidelines for the compilation of national accounts, to enable international harmonization of economic statistics (Mead, Moses, & Moulton, 2004).

These foundational economic policy paradigm shifts need to happen so that corrections to the cost-benefit ratios of safe E-waste management can occur. Governments could enable E-waste recycling industry growth by licensing, providing enforcement and penalties. With an ensured stream of E-waste by category of E-waste, project feasibility is improved for traditional financiers. At present, missing the economic value proposition, PAG operational profitability remains challenging, even for the industry-acknowledged premier manufacturer, Alter NRG, a Canadian company that now owns Westinghouse Plasma. A typical utility-scale PAG plant costs \$1 million to \$300 to implement. Project financing remains difficult despite a tipping point already being reached – processing waste into energy is on-par with landfilling, primarily because land is scarce (Sims, 2016).

The most disadvantaged communities (globally, not just in China) subsidize the costs of both electrical and electronics products manufacturing, as well as end-of-life product dismantling. Consumers and corporations benefit from externalizing their costs to marginalized workers and their families. However, marginalized communities subsidize those externalized costs by paying with their own health, and even their own lives. The most vulnerable of the poor pay first – pregnant women, children, and the elderly.

This study hypothesized that localizing Taiwan's SMM system to China's gray E-waste markets can ultimately help reduce epidemiological risks of primitive E-waste dismantling, by employing PAG processes to convert processed E-waste into usable energy.

The most important application of localizing Taiwan's SMM system to China's market conditions is controlling E-waste flows – by leveraging GPS tracking of cargo container shipments and delivery trucks to ensure E-waste reaches properly authorized treatment centers, instead of being diverted to gray-market micro-business dismantlers who lack protective equipment and effective facilities to maximize metal retrieval and energy production. As part of the solution, this study proposes cloud-based, mirrored-server repositories of 24/7 live video feeds for documentation that E-waste arrives at the proper destinations.

This study determined the stage of primitive E-waste dismantling that first produces major emissions of fine, airborne toxic particles is the mechanical shredding step. Typically in Guiyu and similar micro-businesses in China, shredders are low-quality, older, inefficient machines without covers to prevent shredded dust particles



from becoming airborne and settling in waterways, soil, and human organs.

The specific toxicology of this very recent E-waste phenomenon is complex and unprecedented in human history. E-waste toxic heavy metals and organic compounds are released as mixtures, and the human body burdens cannot be examined in isolation, due to the multiple routes of exposure, chronic and acute exposure, as well as possible inhibitory, synergistic, or addictive effects of exposures, which are all critical variables (Song, 2014).

Researchers have conducted documented, systematic reviews of peer-reviewed research studies investigating the human health consequences of E-waste exposure in China, and their findings conclude that the cumulative data suggests E-waste is harmful to human health, and more well designed epidemiological investigations are needed to confirm these associations, especially in vulnerable populations of pregnant women and children. Grant et al examined 165 selected research articles in any language, and had non-English research articles translated. Song et al examined 52 selected research articles in English and Chinese. In these studies, it was recognized that illegally conducted processes are a large contributory variable to impact consequences (Grant, et al., 2013; Song, 2014). This study focused upon applying SMM systems to increase control over E-waste flows.

Compounding the damage control problem is Guiyu's source of electricity. Fossil fuels (low-grade lignite coal and petroleum) are used to generate the electricity needed to run shredding machines, as well as the proposed PAG systems. China's coal-mining processes for the electricity grids are also heavily damaging to ecosystems. The dominant use of dirty fuels to power low-quality shredding machines in all areas similar

to Guiyu creates greenhouse gas and particulate matter emissions, and adds to the total human health and environmental costs (Song, Wang, Li, & Zeng, 2013). The solution is to avoid using electricity in China that is generated by fossil fuels, or wholly avoid E-waste processes requiring electricity in China. This study focused upon the variable of electricity use in China E-waste shredding compared to the rest of the world.

This study selected the first stage of emissions, mechanical shredding of E-waste, for a LCIA to help provide human health, environmental, and resource impact factor support to decision-makers. Policy-makers need reliable data about cost-benefit value propositions to determine how to best cost-efficiently extract valuable metals, and properly convert remaining E-waste, such as high-calorific value plastics, to usable energy without generating any additional toxic emissions. This study used SimaPro 8.0.5.13 and the Ecoinvent 3 database to conduct the LCIA on 1 kg of heterogenous E-waste, using ReCiPe Endpoint (H) V1.12 / Europe ReCiPe H/A method.

The LCIA uncertainty analyses are acceptably reliable – and uniform in indicators showing business-as-usual (BAC) dismantling recycling activities in China are heavily damaging to human health (Figure 16, Figure 17; Appendix).

The variable selected for comparison was the use of high voltage electricity in China, compared to the rest of the world collectively as a general average, in the mechanical shredding of 1 kg of heterogenous E-waste. The data in Ecoinvent was collected in St. Gallen, Switzerland, and was used to substitute for missing China data. The technology used was characterized as “Typical data of current machines sold for the mechanical treatment of WEEE devices”, and stated as “Modern Shredder facility with shredder, 2 magnetic separation & 2 Eddy-current separation steps” [sic].

Researchers have concluded that, based upon documented systematic reviews of 250 LCIA of thermal waste-to-energy technologies (including plasma arc gasification) published in 136 peer-reviewed journals between 1995 to 2013, very few peer-reviewed research studies provided full and transparent description of critical LCIA aspects, thereby preventing evaluation of the validity of LCIA results. Goal and scope, lack of state-of-the-art technology, descriptions of technology used and underlying inventory data assumptions were not detailed, and modeling approaches were missing data as well, preventing independent validation of calculations. It was also found that few studies investigated gasification in comparison with other thermal processes, and as a whole, the quality of the peer-review process of WtE LCIA studies in scientific journals was “questionable.”

Still, researchers suggested that gasification appeared better in respect to toxic emissions avoidance, due to the advanced metal recovery system available from PAG output of slag (Astrup, Tonini, Turconi, & Boldrin, 2014). This study selected the leading PAG torch manufacturer, AlterNRG, and publicly available data from AlterNRG about its plasma torches was used, which are readily scalable (Figure 21, Figure 22, Appendix). Japan leads the world in processing over 40 million tons of waste annually using thermal treatment. China has over 50 WtE plants. Globally, over 100 thermal treatment plants using different technologies have been recorded. As these utility-sized plants reach end-of-life (EoL), PAG is increasingly considered to be the best WtE technology for replacement primarily due to the low emissions, but also due to increasing interest in the wide variety of energy output products resulting from PAG processes (Figure 14, Figure 15).



this unfolding crises, into funding solution-oriented researchers who are addressing the widening knowledge gap on three broad fronts – epidemiological, technological, and legislative (including enforcement). The author has developed a comparative model localized for New York, which demonstrates the adaptability of tailoring or localizing Taiwan’s SMM model to Guiyi’s context (Jao, 2012).

Existing workers can be outfitted with hazmat suits, and trained to manage a mobile model of on-site E-waste dump processing; leveraging the existing work that millions of waste pickers have already been doing for years, and integrating them into a formalized recycling sector (GTZ, 2010). Instead of just picking out recyclables, workers could process all the various solid waste types on-site by locating modern gasification technology directly where the dumps are located, and derive additional economic market value while decreasing human health and environmental risks.

Solution-oriented research seeks to find the dismantling stage with the most return on effort. This study focused upon the dismantling stage of waste printed circuit boards because of both prevalence and value: every electronics product contains one, and every PCB contains valuable metals.

Recently, global mining companies and manufacturing conglomerates have been investigating how to maximize extraction of valuable metals while minimizing net energy use, including using PCB resins as biofeedstock for energy-generation processes. This study focused upon mechanical shredding of PCBs because it is a common key component in every single electrical and electronic device and appliance. Recyclers most desire the metallic fractions, which comprise 28-30% of PCBs by weight. The non-metallic fractions contain polymer, glass fibers, additives, and comprise 70-72% of PCBs

by weight. This is an exciting research area, and policy-developers ought to be appraised of newest advances in “landfill mining”, or “urban mining.”

Standardization of the epidemiological effects of each major E-waste dismantling stage is necessary due to the prevalence of European source data in LCIA's. Significant investment into cradle-to-grave focused technological design can help foster easier dismantling processes and the growth of the industry as a whole.

Corporate responsibility departments should not be an afterthought, but well-staffed to manage producer responsibility take-back programs of their products when new replacements are purchased. In the U.S., so far only 25 states have passed legislation mandating statewide E-waste recycling (Electronics TakeBack Coalition, 2015). These are missed opportunities for policy-developers seeking new industrial growth at state-levels, particularly states with the headquarters of corporate producers. States can find opportunities in modeling localized policies by drawing from Taiwan's best-case SMM example. Knowledge transfer between renewable energy policy-makers are available to researchers providing decision-making support to policy-makers and private industry – MOEA's Industrial Development Bureau and Bureau of Energy, the Bureau of Energy, TEPA, MENR.

It is proposed that China's central government investigate localizing Taiwan's successful smart materials management (SMM) system, including the complete GPS monitoring system, to enable controlling PCB waste streams away from smugglers and the grey market, and directing smaller “intermixed” E-waste shipments instead to the nascent “formal recycling” industrial sector currently subsidized by the Chinese government. With the implementation of “National Pilot Projects”, the Chinese central

government has sought to identify both logistical challenges and subsidy incentives to controlling E-waste stream channels in targeted cities – Beijing, Tianjin, Qingdao; as well as Zhejiang Province. In response to these movements for enforcing customs regulations, other illegal and grey market shipment channels have increased their efforts circumventing regulatory controls and avoiding fines (UNU, 2013).

It is further proposed that Chinese government agencies and enterprises partner with leading metallurgical corporations to facilitate co-managed delivery of PCBs to dismantling and treatment facilities, and that it be required for metallurgical corporations involved in the scheme to transform processed-PCB plastic residue and processed anode slime into energy.

## Appendix

Table 9. Types of printed circuit boards (PCBs). Adapted from (European Flame Retardants Association, 2015).

Type of PCB	Main material	Application
FR-2	Paper/Phenolic	Paper bonded with plasticized phenol formaldehyde resin. For low-end consumer electronic equipment.
FR-4	Fiberglass/Epoxy	Fiberglass woven cloth bonded with epoxy resin. Flame resistant to the extent of being self-extinguishing. High mechanical strength. Commonly used as electrical insulator in dry and humid conditions. More than 90% of these circuit boards are based on brominated epoxies.
FR-4	Resin/Polytetrafluoroethylene (PTFE)	Resin with brominated or phosphorous-based flame retardants. Sometimes metal oxides are added for higher thermal stability in mobile phones, cameras. Typically used for ultra-high performance applications requiring especially demanding electrical properties – low dielectric permittivity (Dk), low loss tangent (Df) – particularly for computer servers, aerospace and military equipment.



Table 10. Chemicals associated with E-waste and potential health risks (Grant, et al., 2013).

Exposure	Reported levels in Human Populations in E-Waste Recycling Areas	Tolerable Daily Intake estimates	Health Effects and Altered Mechanisms of Action (Animal/ <i>in vitro</i> /human)
Polybrominated diphenyl ethers (PBDEs)	<p>China:</p> <p>Guiyu – blood serum: range 77-8452 ng/g lipid weight<sup>1</sup>, umbilical cord blood levels: range 1.14-504.97 ng/g lipid weight<sup>2</sup>, blood serum BDE 209: max 3100 ng/g lipid weight<sup>3</sup></p> <p>Taizhou – breast milk: range 8.89-457 ng/g lipid weight, placental: range 1.28-72.1 ng/g lipid weight, hair: range 8.47-486 ng/g dry weight<sup>4</sup></p> <p>Guangdong – blood serum BDE 209: max 3436 ng/g lipid weight<sup>5</sup></p> <p>Korea:</p> <p>Seoul – blood serum: range 8.61-46.05 ng/g lipid weight<sup>6</sup></p>	<p>Pentabromodiphenyl ether TDI oral 0.00044 mg/kg bw-d<sup>7</sup>, Octabromodiphenyl ether TDI oral 0.00062 mg/kg bw-d<sup>7</sup>, TDI oral Decabromodiphenyl ether 0.01 mg/kg bw-d<sup>7</sup></p>	Possibly carcinogenic <sup>8</sup>
			Genotoxic <sup>9</sup>
			Endocrine disrupting <sup>10,14</sup>
			Type II diabetes, metabolic syndromes and increased waist circumference <sup>15</sup>
			Low birth weight <sup>16</sup>
			Decrease in IQ <sup>17,18</sup>
			Decreased psychomotor and mental development <sup>18</sup>
			Neurobehavioral development (poorer attention, reduced fine motor coordination, slower processing speed, impaired perceptual reasoning and poorer verbal comprehension) <sup>17</sup>
Polychlorinated Biphenyls (PCBs)	<p>China:</p> <p>Southern China - <math>\Sigma</math>TEQ PCBs: 0.022 pg WHO-TEQ/g<sup>20</sup></p> <p>Guiyu – median serum: 338.56 ng/g lipid weight<sup>21</sup></p> <p>Luqiao – mean serum: 484 ng/g lipid weight<sup>22</sup>, mean serum: 204.20 ng/g lipid weight (Zhao 2010), mean serum: 190 ug/kg lipid<sup>23</sup>, mean umbilical cord: 566.8 ug/kg lipid<sup>23</sup>, pooled mean serum: 40.6 ng/g lipid weight, WHO-TEQ 11.9 pg/g lipid<sup>24</sup></p> <p>Xingui (Zhejiang) – hair maximum: 181.99 ng/g dw<sup>25</sup></p> <p>Philippines:</p> <p>Payatas – breastmilk median: 70 ng/g lipid weight<sup>26</sup></p>	<p>TDI child 0.00013 mg/kg-d<sup>27</sup>, TEF of dioxin-like PCBs calculated in relation to TCDD</p>	Probably carcinogenic <sup>28</sup> , Non-Hodgkin's Lymphoma <sup>29</sup>
			Thyroid function (primarily animal and <i>in vitro</i> ) <sup>30,31</sup>
			Cognitive function and development <sup>32,34</sup>
			Neuropsychological development <sup>35</sup>
			Intellectual impairment (Verbal abstraction, reading comprehension, vocabulary) <sup>32</sup>
			Decrease in IQ <sup>32</sup>
			Attention deficits (animal and potentially in humans) <sup>36</sup>
			Tumour promoters in liver (animal trials) <sup>37</sup>
Dioxins (PCDD/F, PCDFs and TCDD)	<p>China:</p> <p>Southern China – tolerable daily intake: median <math>\Sigma</math>TEQ 0.041 pg TEQ/g</p> <p>Taizhou (Luqiao) – pooled serum: 206 pg/g lipid weight, tolerable daily intake 67.65 pg TEQ/kg body weight/day</p> <p>Taizhou – hair: range 126-5820 pg/g dry weight, tolerable daily intake: summer 0.45, winter 0.39 pg TEQ/Mg</p>	<p>TEF calculated in relation to TCDD</p>	Lower head circumference at birth
			Impaired fetal growth
			Potentially type II diabetes (women)
			Hypertension
			Increased sperm sex chromosome disomy
			Carcinogenic (TCDD) Hodgkin's lymphoma, non-Hodgkin's lymphoma, multiple myeloma, potentially thyroid, rectum and respiratory (males), binary tract and liver (females)
			Thyroid function
			Type II diabetes, Obesity, cardiovascular disease
Perfluoroalkyls (PFOAs)		<p>TDI oral 0.0015 mg/kg bw-d</p>	Chloracne
			Adverse neonatal health outcomes
			Semen quality and sperm count (TCDD)
			Delayed male puberty and testicular maturation
			Potentially endometriosis (TCDD)
			Changes in sex ratio at birth
			Obesity (in prenatally exposed female offspring) (animal)
			Low birth weight
Polycyclic Aromatic Hydrocarbons (PAHs)	<p>China:</p> <p>Guiyu – median <math>\Sigma</math>PAH: 108.05 ppb</p>	<p>Tolerable daily intake estimates have not been determined</p>	Hormone and metabolism alterations (animal)
			Lower overall sperm quality
			Carcinogenic (Some possibly carcinogenic and some probably carcinogens) Lung, skin and bladder. Potentially larynx and kidney
			Mutagenetic

			Immunotoxic Low birth weight, birth length and head circumference Decrease in IQ Genotoxic (lung)
Lead (Pb)	China: Southern China – median serum: 11.449 ug/dL  Guiyu – placental: range 6.51-3465.16 ng/g, serum: range 4.0-48.5 mg/dL (Liu 2011), cord serum: median 10.78 g/dL  Taizhou – serum: 8.11 ug/dL (Lanxi), 6.97 ug/dL (Luqiao)	Currently under review by Health Canada. US EPA has determined it impossible to calculate a threshold figure	Decrease in IQ Impaired cognitive function Neuropsychological function Anemia Behavioral disturbances, hyperactivity and attention deficits Delayed puberty (female) Nephrotoxic Hypertension (in older women) Potential increased risk of Parkinson's Adult hearing loss (in association with cadmium exposure) Schizophrenia (when combined with genetic factors)
Chromium/hexavalent chromium (Cr/Cr(VI))	China: Guiyu – mean umbilical cord blood level: 303.38 ug/L, median serum: 35.5 ug/L	Chromium III TDI oral 1.5 mg/kg-d, Chromium VI TDI oral 0.003 mg/kg-d, Chromium VI TDI inhalation 0.0001 mg/m, Chromium TDI child 0.001 mg/kg-d	Carcinogenic (Cr(VI)) Lung, kidney, prostate Genotoxic Mutagenic Ovotoxic (animal) Reproductive developmental anomalies (animal) Allergic reaction and contact dermatitis
Cadmium (Cd)	China: Southern China – median serum: 1.840 ug/L Guiyu – median umbilical cord serum: 3.61 ug/L, median placental: 0.17 ug/g, median serum: 83.99 ng/g	TDI oral (water) 0.0005 mg/kg-d, TDI oral (food) 0.001 mg/kg-d, TDI inhalation 0.00002 mg/m <sup>3</sup>	Decreased bone density Increased risk of osteoporosis and osteomalacia Nephrotoxic through renal tubular dysfunction Carcinogenic Lung Mutagenic Decrease in IQ Neurodevelopment Adult hearing loss (in association with lead exposure) Possibly hypertension Low birth weight (female infants) Lung damage Liver damage (animal and potentially human)
Copper (Cu)	China: Median serum: 841.5 ug/L Taizhou – hair: 39.8 mg/g dry weight	TDI oral 0.04 mg/kg-d	Reduced lung function Genotoxic Cytotoxic (in vitro and animal)
Nickel (Ni)	China: Guiyu – placental range: 1.76-593.70 ng/g, median serum: 5.3 ug/L	TDI oral 0.02 mg/kg-d	Possibly carcinogenic (Metallic Ni) Lung and nasal Genotoxic Liver damage
Iron (Fe)		TDI oral 0.7 mg/kg-d	Liver damage Genotoxic Cytotoxic

Arsenic (As)		TDI oral 0.0003 mg/kg-d <sup>135</sup>	Skin lesions <sup>133, 134</sup>
			Carcinogenic <sup>135</sup>
			Neurobehavioral development (Motor speed, attention deficits, language deficits) <sup>136</sup>
			Foetal toxicity and birth outcomes <sup>137-139</sup>
			Vascular disease (Ischemic heart disease, carotid atherosclerosis) <sup>140, 141</sup>
			Lung function <sup>133, 142</sup>
			Potentially type II diabetes <sup>143-145</sup>
Mercury (Hg)		Mercury (inorganic) TDI oral 0.0003 mg/kg-d <sup>147</sup> , Methylmercury TDI oral 0.00047 mg/kg-d <sup>147</sup> Methylmercury TDI child 0.0002 mg/kg-d <sup>147</sup>	Nephrotoxic <sup>146</sup>
			Pancreatic damage (animal) <sup>147</sup>
			Impaired cardiovascular homeostasis <sup>148</sup>
			Acute myocardial infarction (methylmercury) <sup>149</sup>
			Immune system toxicity <sup>150, 151</sup>
			Reduced motor control <sup>152</sup>
			Decrease in IQ <sup>153, 154</sup>
			Impaired cognitive function <sup>154</sup>
			Behavioural disturbances and attention deficit hyperactivity disorder (ADHD) <sup>155</sup>
			Potentially autism spectrum disorders ( <i>in vitro</i> and animal) <sup>156, 157</sup>
			Memory loss and potentially a role in Alzheimer's disease <sup>158</sup>
Zinc (Zn)	China: Guangdong – hair: ecological exposure	TDI oral 0.3 mg/kg-d <sup>159</sup> , TDI child oral 0.48 mg/kg-d <sup>157</sup>	Genotoxic <sup>159-161</sup>
			Decreased fertility (female) <sup>162, 163</sup>
			Corrosive substance (gastrointestinal tract) <sup>166</sup>

	112.51 ug/g occupational exposure 138.95 ug/g		Temporarily reduced lung function. Metal fume fever
Lithium (Li)		TDI oral 0.002 mg/kg-d	Lung damage
Beryllium (Be)		TDI oral 0.002 mg/kg-d, TDI inhalation 0.0002 mg/m <sup>3</sup>	Beryllium sensitization (BeH) and Chronic Beryllium disease (CBD)
			Carcinogenic
Barium (Ba)		TDI oral 0.2 mg/kg-d, TDI inhalation 0.0005 mg/m <sup>3</sup>	Cardiovascular effects (animal)
			Potentially a role in the development of neurodegenerative diseases. Multiple sclerosis
Aluminum (Al)		TDI oral 1 mg/kg-d, TDI inhalation 0.005 mg/m <sup>3</sup>	Potentially neurotoxic
			Increase in functional disorders of the nervous system (headache, vertigo, increased emotional irritability, dysmesia, concentration difficulties, sleep disturbance (insomnia and sleepiness), anxiety and fear)
			Oxidative stress in brain tissue. May have an impact on the development of Alzheimer's
			Genotoxic
			Cytotoxic
Manganese (Mn)			Genotoxic
			Cytotoxic
			Potentially Thyroid function
			Neurotoxic (motor skills, psychological disturbances, tremors)
			Attention deficits and hyperactivity

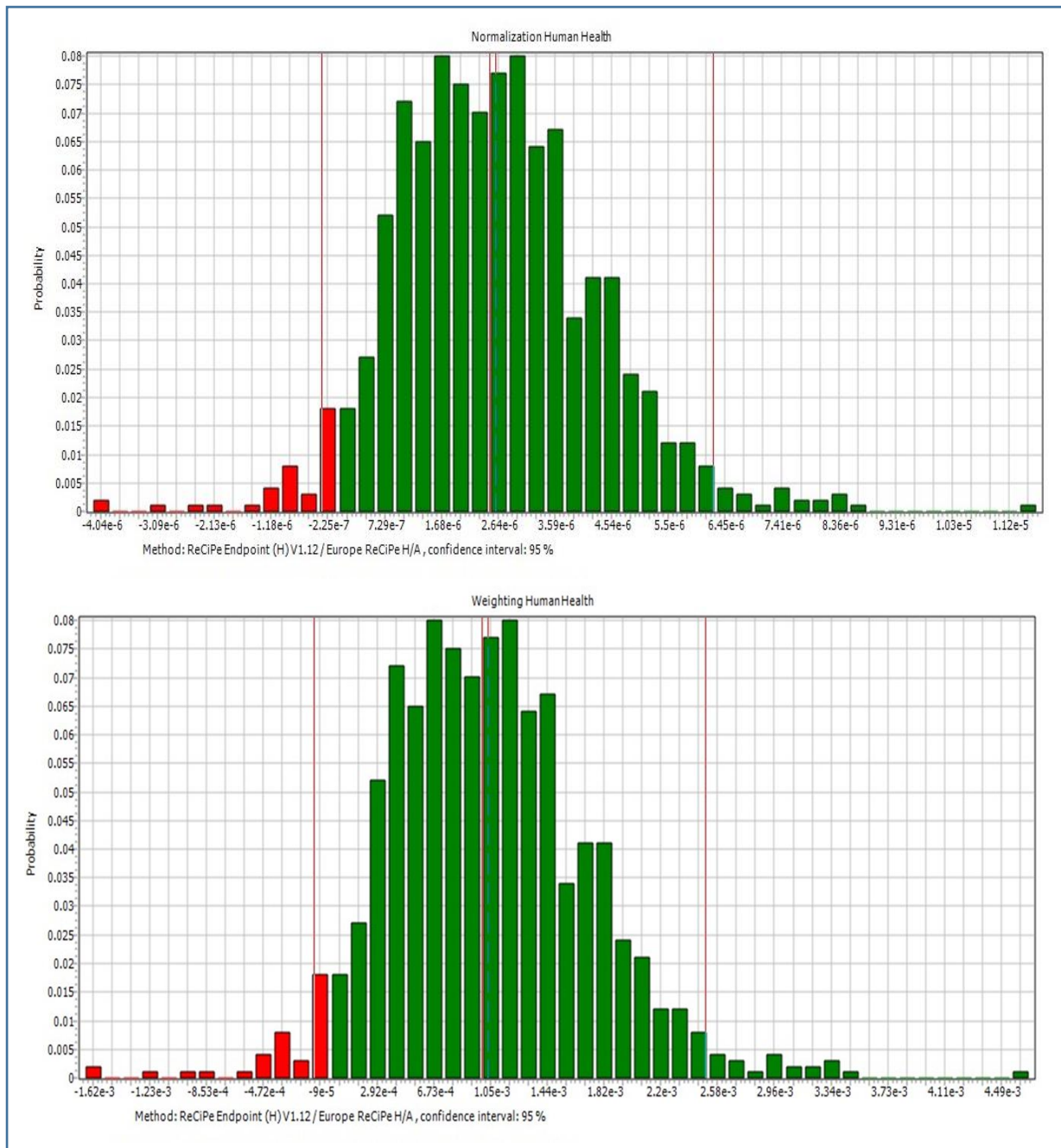


Figure 16. Uncertainty characterization results, normalized and weighted. Using ReCiPe endpoint method, for business-as-usual (BAU) E-waste recycling in China versus rest of world: normalized (per impact categories for China versus rest of world) and weighted (single-score for China versus rest of world). Shows conclusions drawn in this study are reasonably acceptable: BAU E-waste dismantling in China has a significant impact upon human health.

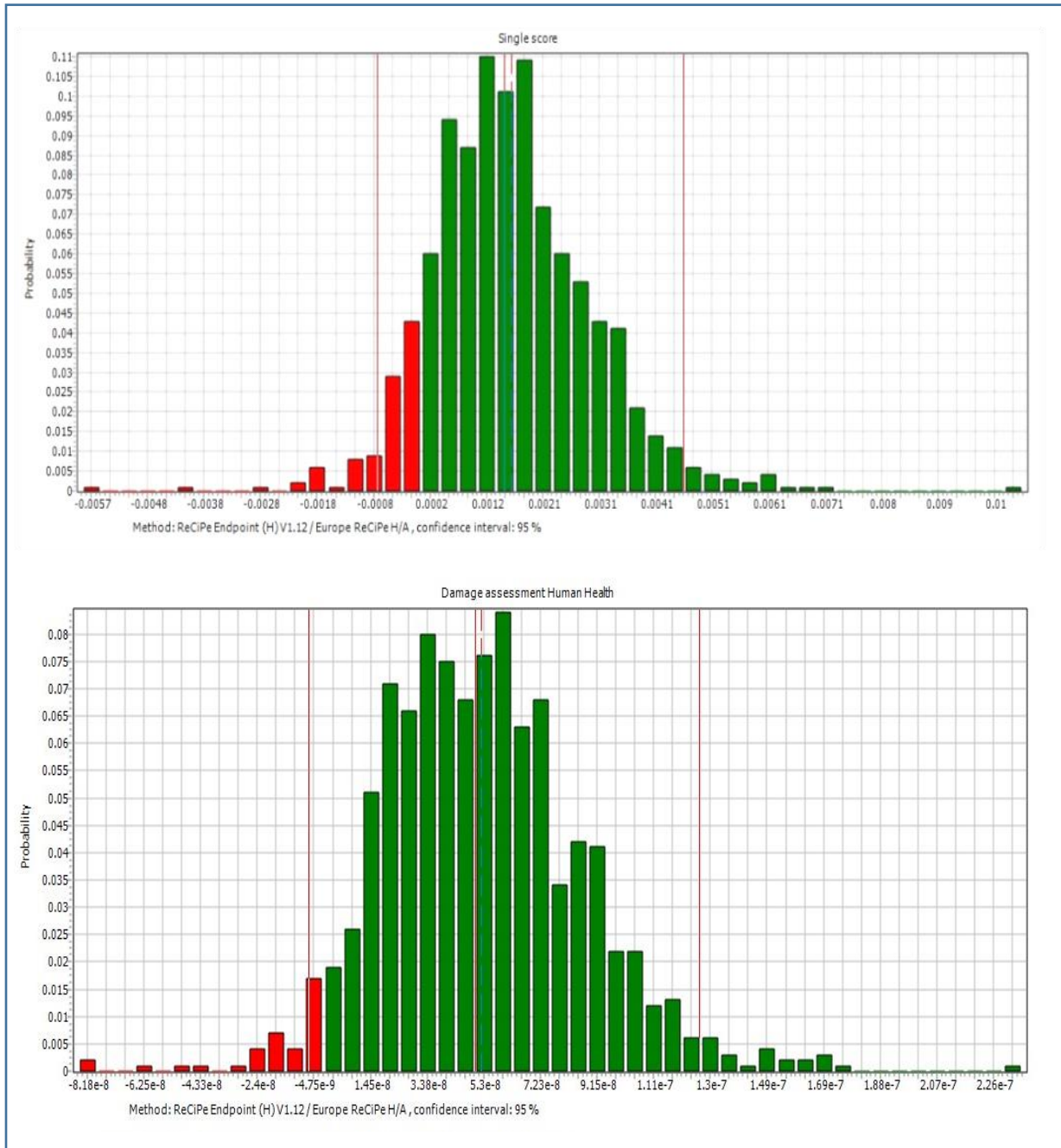


Figure 17. Uncertainty characterization results, single-score and damage assessment. Using ReCiPe endpoint method, for business-as-usual (BAU) E-waste recycling in China versus rest of world: single-score compared to damage assessment of human health. Shows conclusions drawn in this study are reasonably acceptable: BAU E-waste dismantling in China has a significant impact upon human health.



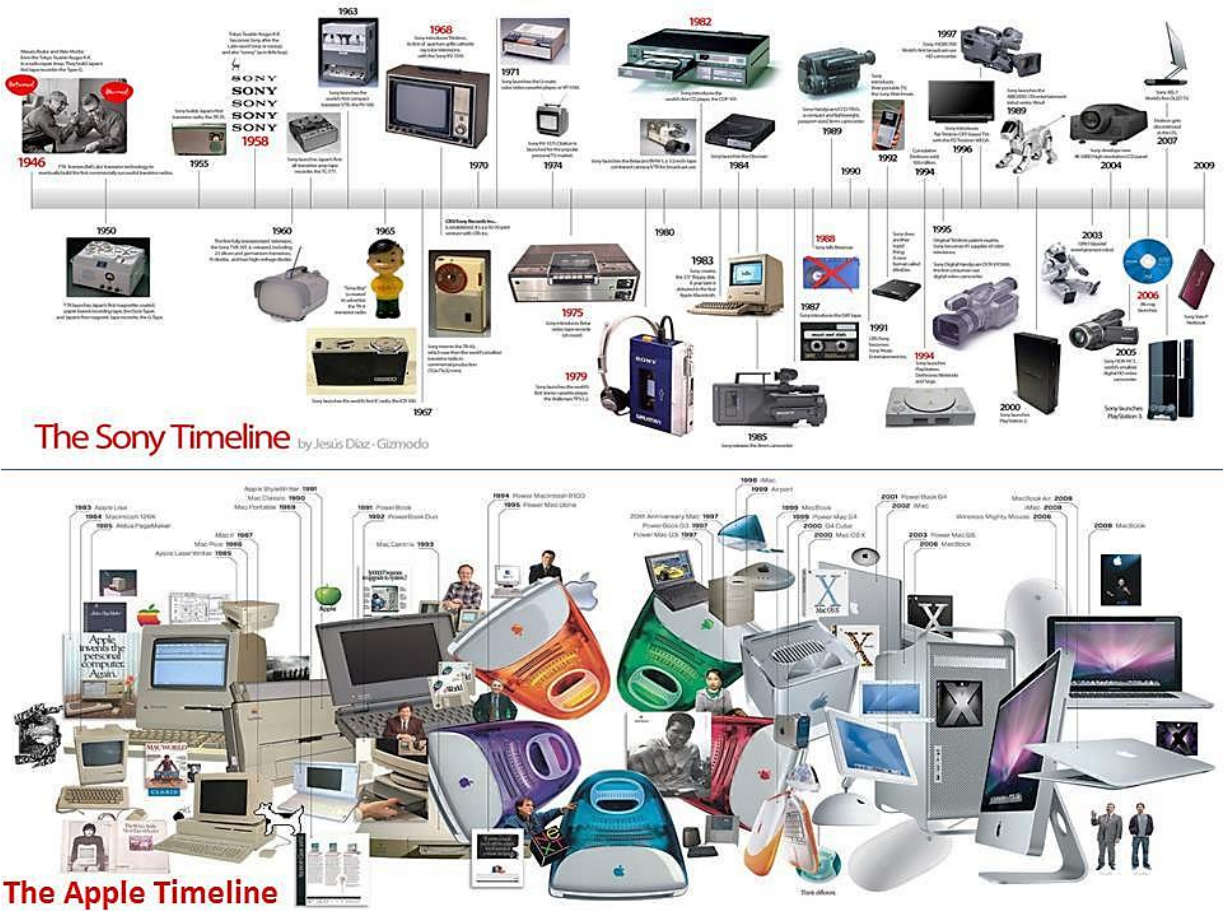


Figure 18. Sony & Apple timeline of products. Technology products proliferation globally appear to be accelerating and growing exponentially. Compiled from (Govindarajan, 2011; Visual.ly, 2013)



Figure 19. E-waste Workers in China “cooking” printed circuit boards (Basel Action Network, 2011)





Figure 20. Plasma arc torch. (AlterNRG, 2015)



Figure 21. Utility scale waste-to-energy plant. (WMW, 2012)





Figure 22. Prototypes of mobile plasma arc gasification modular units. (Rhodes, 2007).

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